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SPECIAL FEATURES OF THE HYDROGEN-DIESEL ENGINE WORKING PROCESS

The works related to the research of the problems and prospects of a hydrogen-fueled reciprocating engine, published so far, mainly relate to the use of hydrogen in spark-ignition engines. Developments of BMW, Toyota and other manufacturers are used in production car models. However, despite a number of advantages, serial production of hydrogen-diesel engines does not yet exist. This paper presents some results of the study of the working process features of a hydrogen-diesel engine with direct injection of hydrogen gas, analyzes the problems and prospects of the concept of the hydrogen-diesel engine. The obtained results of 3D modelling of the working process and experimental research prove the prospects and reality of the implementation of the hydrogen-diesel engine concept.

Keywords: *hydrogen-diesel engine, direct injection, nitrogen oxides, 3D modelling*

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Introduction. The solution of two global problems of modern civilization, environmental and energy problems, is directly related to internal combustion engines (ICE), the main consumers of petroleum-derived fuels and active environmental pollutants. Reciprocating engine manufacture currently implies the development of the following concepts for creating promising ICE [1–6]:

1) traditional engines with alternative fuel;
2) alternative engines with traditional fuel;
3) alternative engines with alternative fuel;
4) an alternative, for example, electric drive;

and of course, different combinations of these concepts.

Concepts 2) and 3) have no prospects unless an alternative thermal engine is created that has an efficiency higher than that of modern ICE, for example, diesels, which is unlikely in the near future. The first concept is supported by the highest efficiency among all thermal engines and the potential of modern technologies to organize the production of alternative fuels, and in the future to develop artificial motor fuels with the desired thermal and physical characteristics. The concept of an electric drive will find its niche for movement over relatively short distances, as well as where small capacities are required, for example, urban transport. However, complete electrification of road transport is currently impossible: cars consume more energy than all power plants in the world, including nuclear ones, generate. The full provision of the car fleet with electricity is apparently postponed until the introduction of fusion energetics, the prospects of which are still vague. But internal combustion engines are not only car engines. It is difficult to imagine that large marine diesels, for example, Wartsila-Sulzer 14RTA96-C type (number of cylinders i = 14; cylinder diameter D = 0.96 m; piston distance S = 2.5 m; cylinder cubic capacity V_h = 25,480 l; effective engine power Ne = 80,100 kW with crankshaft rotation frequency n = 102 rpm) with a dry weight of 2,300 t will be replaced by an electric drive. In addition, recent disasters related to floods, including in Europe, have shown the complete unsuitability of electric motor vehicles for rescue operations.

Hydrogen is considered to be the most promising alternative fuel currently known, which is primarily due to the unique properties of hydrogen as a motor fuel: high combustion value (about 3 times more than traditional fuels) and wide ignition limits by air excess value (for hydrogen α_a = 0.13–10.0; for diesel fuel α_a = 0.48–1.35). Hydrogen in the gas or liquid state in reciprocating engines can be realized on the basis of the following conceptual approaches [6–9]:

- traditional engines (gasoline and diesel engines) using hydrogen as a small additive to the main fuel;
- hydrogen-fueled engine with external mixture formation and forced ignition of a hydrogen-air mixture;

- hydrogen-diesel engine with direct injection of hydrogen; the first two concepts, unlike the last one, are sufficiently researched.

Advantages of the hydrogen-diesel engine concept with direct injection. In addition to such well-known advantages of diesel as high-quality power control, high fuel efficiency, no knocking and the possibility of high-pressure charging, the concept of a hydrogen-diesel engine with direct injection of hydrogen gas into the cylinder is characterized by [9]:

- the high values of the efficiency coefficient of the thermodynamic cycle and the coefficient of molecular change;
- the complete decarbonization of exhaust gases in which there are no harmful substances limited by legislation: unburned hydrocarbons HC, CO, solid particles, as well as "greenhouse" gas CO_2;
- the absence of disadvantages inherent in hydrogen-fueled engines with external mixture formation and spark ignition: the probability of detonation, preignition, backfire (ignition of a fresh charge in the intake system during the opening of the intake organs, the causes of which may be aftercombustion, high temperature of residual combustion products, an excessively long period of overlap of the intake and exhaust processes, etc.);
- compared to modern engines with forced ignition of liquid hydrogen (for example, BMW 750HL) — the absence of expensive cryogenic technology;
- the possibility of high-quality power control (compared to external mixture formation).

Due to the low density (in the liquid state, about 10 times less than that of gasoline), hydrogen occupies a larger volume than the equivalent amount of gasoline in terms of energy content. Therefore, the maximum value of the average indicator pressure p_i in the case of gasoline is about 20–25 % higher compared to hydrogen. In order to compensate for the loss of power during the transition from gasoline to hydrogen in the ICE with external mixture formation, an increase in V_h is required. When switching to internal mixture formation with hydrogen, it is possible not only to avoid a decrease in p_i, but also to increase it.

Problems of implementing an efficient and environmentally friendly working process of hydrogen-diesel engine. The reason that the concept of a hydrogen-diesel engine with direct injection of hydrogen gas has been little studied to date is, first of all, the possibility of high-quality power control in engines with external mixture formation, associated with wide ignition limits of the hydrogen-air mixture, and the desire on this basis to increase efficiency to the level of diesel. Let us note that the conversion of traditional diesel to hydrogen requires solving problems related to:

- the need to increase the compression ratio ε in order to provide an air temperature sufficient for self-ignition of hydrogen (T = 585 °C in air at p = 1.013 bar), which is higher than the self-ignition temperature of diesel fuel (T = 250 °C under the same conditions [5, 6]). The increase in the compression ratio in diesel engines is known to be limited by the permissible values of thermal and mechanical loads on the main parts, as well as by a decrease in the volume of the chamber sufficient for high-quality combustion [6];
- the instability of the combustion process in successive operating cycles, expressed in fluctuations in the average effective and maximum pressures of alternating cycles. Preventing this phenomenon by increasing the compression ratio is not advisable for the above mentioned reason. Studies have shown that it is better to use preheating of the intake air [5, 6];
- the inevitability of direct oxidation of nitrogen, which is part of atmospheric air, and the formation of nitrogen oxides. According to the Zeldovich thermal mechanism, intensive NO_x formation occurs at T > 1800 K. The problem is aggravated by the so-called quenching property of nitrogen oxides, the concentration of which grows rapidly with increasing temperature, and then after reaching the maximum, despite the drop in temperature in the cylinder, it practically does not decrease. Thus, from an environmental point of view, the main problem of improving the working process of a hydrogen-diesel engine is to minimize emissions of nitrogen oxides below the level established by legislative acts, as well as to reduce the noise generated by the high rate of pressure build-up due to the rapid combustion of the hydrogen-air mixture. The fact that the product of hydrogen combustion is water should not give rise to unfounded claims, which have been encountered in a number of cases, that hydrogen engines do not pollute the environment and emit only water vapor.

Study of the working process of a hydrogen-fueled engine. The study objects were an experimental four-stroke one-cylinder supercharged diesel engine 1ЧН (1ChN) 30/24 with direct injection of hydrogen gas and its basic version with diesel fuel injection [8]. The one-cylinder compartment of the serial diesel MAN has the following technical data: the ratio of the piston distance and cylinder diameter S/D = 30/24 cm/cm; fuel — diesel/hydrogen gas; crankshaft rotation frequency n = 800/800 rpm; injection pressure p_{inj} = 350/300 bar; compression ratio ε = 13.5/17. Preliminary calculations showed that it was impractical to increase the compression ratio of a hydrogen-diesel engine more than ε = 18. Despite the different compression ratios, both diesels had a Hesselman-type combustion chamber. Unlike the serial diesel equipped with a high-pressure fuel pump, an autonomous hydrogen gas supply system was installed on the hydrogen-diesel engine using a Lucas multi-hole injector (hydraulically driven and electronically controlled). The installation was designed to study the operation of diesel not only on pure hydrogen, but also on other gaseous fuels, including natural gas and synthesis gases with different hydrogen content [8, 10, 11]. The basic diesel had a four-valve cylinder head without a charge swirl and a serial injector $z \times d_n = 4 \times 0.25$ (z is the number of nozzle holes, d_n is their diameter, mm). The cylinder head of the hydrogen-diesel engine is also four-valve, but with an adjustable charge swirl (one of the intake valves has a shield). Special injectors of 5 different designs were used to inject hydrogen gas ($z = 6 \times 0.7$; $z = 12 \times 0.5$; $z = 18 \times 0.5$; $z = 6 \times 0.85$; $z = 4 \times 0.5 + 4 \times 0.7$). The experimental installation was equipped with a boosting system with a heat exchanger for cooling the boost air, which allowed varying the intake air temperature from 20 to 70 °C. During the experiment, the effective indicators of the engine were recorded, hydrogen diesel was indicated, the emission of harmful components of combustion products, and local temperatures on the combustion chamber surface were measured. The obtained experimental values of the parameters were used in the development, as well as for the verification of mathematical models of the workflow.

The basis of the mathematical model of the workflow is a system of fundamental equations of the momentum (Navier-Stokes), energy (Fourier–Kirchhoff), diffusion (Fick) and continuity, written in the form of Reynolds and averaged by Favre. The system of equations is closed using the k-ζ-f turbulence model, which takes into account the specifics of intra-cylinder processes in reciprocating engines [7]. The implementation of the mathematical model is carried out using the 3D CRFD code FIRE [12]. The processes of turbulent combustion and the formation of nitrogen oxides are modelled using the Magnussen-Hjertager model and the extended kinetic mechanism of Zeldovich. Verification of the mathematical model was carried out by comparing the calculated and experimental indicator diagrams, while the values of the empirical coefficients in the Magnussen–Hjertager combustion model were clarified, ensuring good agreement of the calculation results with the indexing results. It should be emphasized that a comparative analysis of the effective and environmental parameters of the basic and hydrogen-diesel engines was carried out with an approximate equality of their effective power.

Features of the working process of hydrogen-diesel engine. It has been established that the processes of ignition and combustion in hydrogen-fueled and conventional diesel engines are significantly different. It is explained, first of all, by different phase states (gas and liquid) of fuels in these engines. In the case of diesel fuel, intensive processes of evaporation and diffusion with air (i.e. mixture formation) occur on the outer surface of the fuel jet, where ignition sites occur. In the area of the fuel flame cone, the combustion process develops with some delay. Injected hydrogen gas, on the contrary, diffuses faster with air almost throughout the entire volume of the hydrogen torch and ignites faster than diesel fuel. At the same time, the flame front rapidly covers almost the entire volume of the combustion chamber. Such a difference in the course of the processes of mixture formation and combustion leads to the fact that the processes of changing the local temperatures of the working fluid and local concentrations of nitrogen oxides in the combustion chambers of hydrogen-fueled and basic diesel engines in similar operating modes proceed differently. In the case of diesel fuel, local ignition processes are concentrated in the area of the outer surface, and combustion processes are focused in the area of the fuel flame cone. Hydrogen is characterized by faster ignition, while the flame front rapidly covers almost the entire volume of the combustion chamber. In this regard, the nature of changes in local temperatures and, consequently, local concentrations of nitrogen oxides in the combustion chambers of these diesels differs.

In the hydrogen-diesel engine, thermal loads on the main parts can increase, which is due to the absence of a heat-insulating layer of carbon deposits on the heat absorption areas of engine parts and the presence of high gas temperatures in the cylinder due to a reduction in the duration of combustion. Onthe other hand, the absence of solid soot particles in the combustion chamber of a hydrogen-diesel engine, the main radiation generators leads to the fact that the radiant heat flux on the heat absorption areas of the combustion chamber is generated only by high-temperature gases, i.e. negligible in comparison with convective heat flux [13]. In general, the specific course of combustion and heat generation processes in a hydrogen-diesel engine leads to an increase in thermal loads on the main engine parts. It is established that for the investigated hydrogen-diesel engine, the most significant increase in the thermal load is on the surface of the cylinder head, which indicates the need to intensify the cooling of the head in order to preserve the engine life. In the case of hydrogen gas injection twice per cycle (pilot injection + main injection), the thermal loads on the parts of the combustion chamber of a hydrogen-diesel engine are reduced by an average of 17 %. Change in the moment of supply of the pilot dose of hydrogen $\varphi_{p.inj}$ from 330 to 338° increases the value of the local heat transfer coefficient α from 2900 to 3500 W/(m^{2}K) (the zone in the center of the piston firing bottom). Due to the design limitations of the engine under study at the level of the maximum cycle pressure $p_z = 150$ bar during pilot injection, it is recommended to reduce the cyclic supply of hydrogen gas.

Different rates of heat release in the combustion chambers of the basic diesel and its hydrogen modification lead to the fact that the processes of local formation of nitrogen oxides in a hydrogen diesel occur with greater intensity, however, the total emissions of nitrogen oxides in both engines during the cycle, with equal effective capacities, have approximately the same level.

Studies of 5 variants of the injector sprayer nozzle showed that the number, diameter and total area of the flow passages significantly affect the formation of nitrogen oxides. The maximum and minimum values of the total volume of the cylinder mass fractions of nitrogen oxides per cycle are obtained using injectors of 6×0.7 mm and 18×0.5 mm and are $[NO_x]_\Sigma = 0.00158$ and $[NO_x]_\Sigma = 0.00027$, respectively. The remaining injectors give intermediate results. The maximum local values of the mass fractions of nitrogen oxides (in the *i*-th control volume at φ = 365° of the angle of crankshaft rotation reach $[NO_x]_i = 0.005$ and $[NO_x]_i = 0.0035$, respectively. It was found that with an increase in the number of nozzle holes, hydrogen is more evenly distributed over the volume of the combustion chamber, the hydrogen-air mixture is homogenized, the level of local temperatures in the combustion site drops, which leads to a decrease in the NO_x concentration [6, 7].

The dependence of the emission of nitrogen oxides on the mass of hydrogen entering the cylinder was studied for a constant value of the total excess air factor $\alpha_{a\Sigma} = 2$ = const. This condition was met by adjusting the boost pressure. The injection pressure was kept constant by changing the duration of the hydrogen supply. The varied parameters changed within:

- cyclic supply of hydrogen $m_c = 0.33\ldots0.49$ g/cycle;
- duration of hydrogen injection $\Delta\varphi_{\text{inj}} = 30\ldots47°$ of rotation angle;
- boost pressure $p_k = 2\ldots3$ bar.

It is obvious that with an increase in the cyclic supply of hydrogen at $\alpha_{a\Sigma}$ = const, the total mass of the gas (hydrogen-air mixture) in the cylinder and its density increase. Since the injection pressure of hydrogen gas and the kinetic energy of the hydrogen jets do not change when they flow out of the nozzle, the range of the hydrogen torch is reduced. The bulk of hydrogen accumulates in the injector area, and due to the lack of oxygen in this zone, the rate of heat release is noticeably reduced in both the first and second phases of combustion. The stretching of the heat release process leads to a drop in local temperatures in the combustion chamber, and therefore the concentration of nitrogen oxides decreases. In this case, the main proportion of nitrogen oxides is formed in the first (kinetic) phase of the combustion process, approximately at the moment of φ = 365° of the rotation angle. For this moment, an increase in the cyclic supply of hydrogen leads to a decrease in the emission of nitrogen oxides. This makes hydrogen-diesel engine fundamentally different from conventional diesel, where the opposite effect usually takes place [14].

The change in the total excess air factor was carried out within $\alpha_{a\Sigma} = 1.85...2.5$ by adjusting the boost pressure. In this case, the cyclic supply of hydrogen is $m_c = 0.49$ g/cycle = const. It has been established that the phenomenon of a sharp reduction in nitrogen oxide emissions by a strong leaning of the fuel mixture also occurs in hydrogen-diesel engine, however, in the case of hydrogen-diesel engine, this phenomenon does not seem as decisive as, for example, in gas or dual fuel engines.

In a conventional diesel engine, with an optimal value of the turbulence intensity, obtaining a low specific fuel consumption is usually accompanied by an increase in NO_x emissions. In a hydrogen-diesel engine, a significant increase in air swirl contributes to rapid diffusion with hydrogen. Already at the beginning of the supply, hydrogen is so diluted with air that its amount in local zones is below the concentration limits of ignition (approximately less than 4 % by volume) [6]. Self-ignition begins later, after an increase in the concentration of hydrogen, the ignition delay grows, the combustion process is stretched, the maximum heat release rate moves away from the upper dead center, local temperatures of the working fluid decrease and, as a result, emissions of nitrogen oxides drops. In addition, the prolonged process of energy conversion leads to a decrease in the rate of pressure build-up and a drop in noise. However, such a change in the rate of heat release leads to a decrease in the efficiency of the cycle. Thus, an increase in the turbulence intensity of the charge in a hydrogen-diesel engine leads to a deterioration in its effective performance.

Conclusion. The concept of a hydrogen-diesel engine operating by self-ignition of hydrogen gas injected into the pre-compressed hot air is certainly promising, both in terms of efficiency (high fuel efficiency, i.e. high efficiency coefficient) and environmental friendliness (absence of solid particles of soot, CH, CO, as well as "greenhouse" gas CO_2 in the combustion products). The main problem of improving the environmental performance of hydrogen-diesel engine is minimizing the emission of nitrogen oxides, the only harmful components of combustion products which emissions are limited by legislative acts. It can be successfully solved by an optimal combination of design (compression ratio, design and number of injector spray nozzles) and adjustment (intake air temperature, parameters of cyclic hydrogen supply, excess air factor, intensity of charge swirl) parameters. The optimal combination of the working process parameters for the stationary hydrogen-diesel engine under study is the installation of a sprayer for the supply of hydrogen 18×0.5 mm; cyclic supply of hydrogen $m_c = 0.49$ g/cycle; air excess factor $\alpha_a = 2.5$. In this case, the concentration of nitrogen oxides in the combustion products is $[NO_x] = 950$ ppm, and the indicator efficiency of hydrogen-diesel engine is $\eta_i = 0.48$, which is quite acceptable for the type of diesel under study. The conducted research confirms that the hydrogen-diesel engine copes perfectly with modern requirements, both in terms of fuel efficiency and emissions of harmful substances.

The widespread use of hydrogen in diesel engines, as in other heat engines, is hindered by its cost price and explosion hazard in operating conditions. The process of solving these problems will especially accelerate, since hydrogen remains the only real way out of the energy and environmental crises. An important role is played here by the position of the owners of reserves of traditional, hydrocarbon fuels and their producers. On the other hand, the experience of engine building development shows that those problems of cost and safety that are difficult to access today will certainly be overcome, and after a while they will seem simple and easily solved (recall the history of the introduction of gasoline as a motor fuel). The position of hydrogen as a motor fuel of the future is strengthened by Europe's desire to switch to CO_2-neutral energy supply by 2050 [15, 16]. Therefore, the introduction of hydrogen diesel is only a matter of time.

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ОСОБЕННОСТИ РАБОЧЕГО ПРОЦЕССА ВОДОРОДНОГО ДИЗЕЛЯ

Работы, касающиеся исследований проблем и перспектив водородного поршневого двигателя, опубликованные до настоящего времени, в основном относятся к применению водорода в двигателях с искровым зажиганием. Разработки BMW, Toyota и других производителей находят применения *в серийных моделях автомобилей. Однако, несмотря на ряд преимуществ, серийного производства водородных дизелей пока еще не существует. В данной работе приведены некоторые результаты исследования особенностей рабочего процесса водородного дизеля с непосредственным впрыскиванием газообразного водорода, проанализированы проблемы и перспективы концепции водородного дизеля. Полученные результаты 3D-моделирования рабочего процесса и экспериментального исследования доказывают перспективность и реальность осуществления концепции водородного дизеля.*

Ключевые слова: *водородный дизель, непосредственное впрыскивание, оксиды азота, 3D-моделирование*

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