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IMPROVING THE PERFORMANCE CHARACTERISTICS OF A DIESEL ENGINE BY ADDING HYDROGEN TO THE DIESEL–AIR MIXTURE

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Abstract. This article highlights the pressing issues associated with the use of internal combustion diesel engines based on a system analysis approach. The study examines the operating conditions of diesel-powered vehicles in which hydrogen is used as an additive to the fuel–air mixture, ensuring forced combustion. Compared to gas and electric power systems, such an approach provides higher reliability, improved fuel economy, environmental cleanliness, and adaptability to various climatic conditions.

Keywords: diesel engine, system analysis, environmental safety, combustion process, hydrogen additive, combustion phases, effect of hydrogen on soot formation.

ПОВЫШЕНИЕ ЭКСПЛУАТАЦИОННЫХ ПОКАЗАТЕЛЕЙ ДИЗЕЛЬНОГО ДВИГАТЕЛЯ ПУТЁМ ДОБАВЛЕНИЯ ВОДОРОДА В ТОПЛИВНО-ВОЗДУШНУЮ СМЕСЬ

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Аннотация. В данной статье с использованием системного анализа рассматриваются актуальные вопросы эксплуатации дизельных двигателей внутреннего сгорания. Исследованы условия работы дизельных транспортных средств, в которых водород применяется в качестве добавки к топливно-воздушной смеси, обеспечивая принудительное воспламенение. По сравнению с газовыми и электрическими энергетическими установками данный подход отличается более высокой надёжностью, экономичностью, экологической чистотой и адаптацией к различным климатическим условиям.

Ключевые слова: дизельный двигатель, системный анализ, экологическая безопасность, процесс сгорания, добавка водорода, фазы сгорания, влияние водорода на образование сажи.

Introduction.

The utilization of hydrogen in diesel engines is constrained by its high self-ignition temperature. Therefore, to ensure stable combustion of hydrogen, diesel engines employ forced ignition, either by means of a spark plug or through the ignition dose of liquid fuel. In this case, hydrogen can be supplied together with air or directly injected into the cylinders. However, stable operation of a diesel engine with hydrogen is achieved only within a narrow range of fuel mixture compositions, which is limited by the conditions of ignition and detonation [6].

Literature Review.

Analysis of the combustion process shows that the fuel entering the combustion chamber (as presented in Table 1) requires a certain amount of time to completely evaporate and oxidize with oxygen. The longer this period, the greater the deviation of the engine's theoretical parameters and fuel quality from their optimal values. The ignition delay period generally corresponds to a crankshaft rotation angle of 12–25° or 0.001–0.003 s. Table 1 presents the combustion phases and their characteristics within the cylinder of a diesel engine [1].

Table 1.

Combustion phases and characteristics in a diesel engine cylinder

Combustion phase	Crankshaft rotation angle, °φ	Duration, μs	Droplet diameter, μm	Piston movement direction	Pressure, MPa	Temperature, °C
Ignition delay (1st phase)	12–25	0.001–0.003	30–40	Upward	2.5–5	750–1000
Rapid combustion (2nd phase)	10–20	0.008–0.0015	10–20	Upward	6–9	1600–1800
Controlled combustion (3rd phase)	15–25	0.0012	Vapor form	Downward	5.5–8	1800–2200
Afterburning (4th phase)	50–60	0.0035–0.005	Burned fuel	Downward	3–4	630–930

For the H_2–CH_4 mixture, the diffusion coefficient is 62.5 × 10^{-6} m^2/s at 273 K and 72.6 × 10^{-6} m^2/s at 298 K. In general, considering that HHO or hydrogen represents an ideal combination of fuel and oxidizer, it completely burns all exhaust gases without leaving any residues, producing only water vapor (but not oxygen) as the final product [2].

Problem Statement and Objective.

The wide concentration limits of hydrogen combustion in air make it possible to regulate the fuel ignition process in engine combustion chambers with high precision. Due to the feasibility of organizing the working process of internal combustion engines using hydrocarbon–hydrogen mixtures, a number of studies have been carried out to determine the concentration limits of flame propagation in multicomponent combustible gas mixtures.

Experimental data were obtained for the lower concentration limits of flame propagation in CO_2+H_2, CH_4+H_2, and C_3H_8+H_2 air mixtures. The initial temperature of the mixtures was 25 °C. On the abscissa axis of the graphs, the relative volumetric fraction of hydrogen in the composite fuel was denoted as

$[H_2]/[H_2+CO]$, $[H_2]/[H_2+CH_4]$, and $[H_2]/[H_2+C_3H_8]$. Based on these observations, an important conclusion was drawn regarding the applicability of Le Chatelier's empirical rule for estimating the lower flammability limit in combustible air mixtures such as $(CO+H_2)$, (CH_4+H_2), $(C_3H_8+H_2)$, $(CH_4+C_3H_8+H_2)$, and $(CO+CH_4+H_2)$ [3].

The high values of the normal flame propagation velocity, which are strongly dependent on temperature and pressure, reduce the duration of physicochemical combustion processes and positively influence the concentration of NO_x emissions and CH_x compounds in the exhaust gases under optimal mixture conditions. The intensification of these processes, resulting from shorter combustion duration, contributes to improving engine efficiency.

According to various estimates, the maximum normal flame propagation velocity in hydrogen–air mixtures ranges from 24 to 270 cm/s and is highly dependent on temperature (Table 2). The autoignition temperature of hydrogen depends on the mixture composition and for the stoichiometric mixture is approximately 500–510 °C [4].

The maximum velocity does not correspond to the stoichiometric ratio but shifts significantly toward the lean mixture region ($\alpha = 1.7$). Under conditions of high pressure, temperature, and turbulence in the combustion chamber, the combustion rate of hydrogen mixtures is considerably higher than the normal flame propagation velocity. Under these circumstances, the sharp increase in flame propagation rate can cause self-ignition of the mixture in adjacent ignition centers [8].

Table 2.

Dependence of flame propagation velocity on temperature in hydrogen–air mixtures

Mixture temperature, °C	20	100	200	300	400
Flame propagation velocity, m/s	250	400	600	900	1200

Modern data on the combustion rate of diesel–air mixtures at atmospheric pressure and room temperature are presented in [9].

A change in the hydrogen concentration within the (CH_4+H_2) mixture alters the heat release characteristics; in particular, an increase in the hydrogen content sharply reduces the combustion duration.

The high combustion rate of hydrogen–air mixtures and the resulting high rate of pressure rise within the engine cylinders contribute to an increase in the engine's indicated efficiency.

The working process characteristics of an internal combustion engine operating with hydrogen are determined by the properties of the hydrogen–air mixture - the combustion and flame propagation limits, flame temperature, and energy. All these parameters are superior for hydrogen compared to hydrocarbon fuels (Table 3) [10].

Hydrogen, which possesses a significantly higher flame propagation velocity than hydrocarbons, acts as a kind of "pre-combustion" catalyst that ignites the working mixture, ensuring complete combustion within a short time and generating higher pressure and thermal energy. This, in turn, contributes to increased torque. As the fuel burns more completely, the emission of harmful components in the exhaust gases is reduced [14].

Table 3.

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Property	Diesel	Hydrogen
Fuel density, kg/m³	860	0,0899

Minimum ignition energy, MJ	0,23	0,02
Lower heating value, MJ/kg	43,76	120
Stoichiometric air requirement per 1 kg of fuel, kg/kg	14,3	34,3
Maximum laminar flame speed, m/s	0,20	2,75
Diffusion coefficient, cm^2/s	0,078	0,63
Concentration limits of flame propagation, α	α_{max} –0,9; α_{min} –5,0	α_{max} –0,22; α_{min} –4,0

Results.

Hydrogen is almost an ideal type of fuel; however, the main challenge lies in the fact that on our planet, it exists only in combination with other chemical elements. The proportion of "pure" hydrogen in the atmosphere does not exceed 0.00005%. Considering these facts, the issue of developing a hydrogen generator remains highly relevant. The principle of operation, design features, scale, and feasibility of self-manufacturing such a device were examined in this study [11].

There are several methods for separating hydrogen from other substances, among which the most common are as follows:

Electrolysis. This is the simplest method and can even be performed at home. A direct electric current is passed through an aqueous solution containing salt, resulting in a chemical reaction that can be described by the following equation: $2NaCI+2HH_2 \rightarrow 2NaOH+CI_2+H_2\uparrow$.

In this case, a solution of ordinary table salt is used as an example; however, this is not the most favorable option, since the released chlorine is a toxic substance, although the hydrogen obtained by this method is of very high purity (approximately 99.9%).

2. Passing steam over heated coke. When water vapor is passed over coke heated to a temperature of about 1000 °C, the following reaction occurs: $H_2O + C \Leftrightarrow CO\uparrow + H_2\uparrow$.

3. Steam reforming of methane. Hydrogen can be obtained from methane through steam conversion, with the required reaction temperature being approximately 1000 °C: $CH_4 + H_2O \Leftrightarrow CO + 3H_2$.

The second variant is methane oxidation: $2CH4 + O2 \Leftrightarrow 2CO + 4H_2$.

4. During the cracking process (oil refining), hydrogen is released as a by-product. For this purpose, industrial installations for hydrogen production are manufactured, typically in the form of membrane-type electrolyzers. A simplified design and operational principle of such a device are presented in Figure 1 [12].

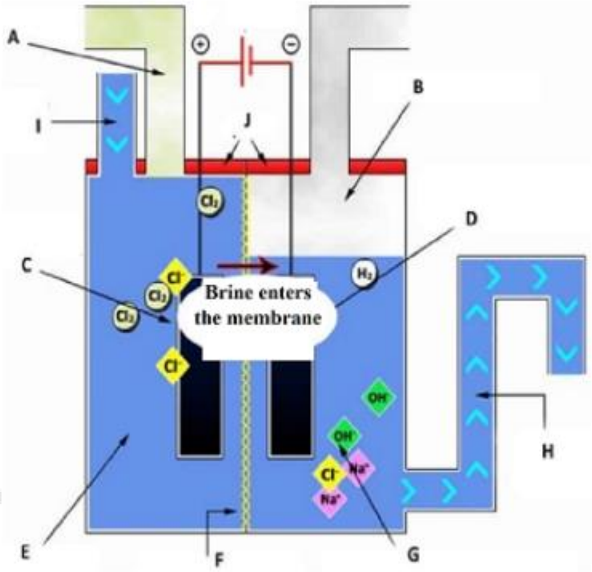

Figure 1. Simplified schematic of a membrane-type hydrogen generator

A - chlorine drain tube (Cl_2); B - hydrogen outlet (H_2); C - anode where the reaction occurs: $2Cl^- \rightarrow Cl_2 + 2e^-$; D - cathode, where the reaction can be described by the following equation: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$; E - water and sodium chloride solution (H_2O & $NaCl$); F - membrane; G - formation of saturated sodium chloride solution and caustic soda ($NaOH$);

H - brine and diluted caustic soda outlet; I - inlet of saturated brine solution; J - cover.

Conclusion

The proposed system consists of hydrogen production equipment (an electrolyzer installed in the engine compartment, alternative energy sources, and an electrical energy accumulator) and pipelines for supplying hydrogen to the power system of the internal combustion engine.

The prospects for using hydrogen as an additive to the main fuel in order to improve the operating cycle parameters of an internal combustion engine are determined by the following factors:

– the possibility of reducing the toxicity of exhaust gases in terms of their main components - CO, CH, and NO_x;

– the reduction of harmful emissions in exhaust gases achieved through increased fuel efficiency;

– the feasibility of implementing the proposed method without significant design modifications to the internal combustion engine.

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