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MECHANICAL AND AERONAUTICAL ENGINEERING

# Advanced fuel system with gaseous hydrogen additives

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**Abstract.** The advancement of contemporary internal combustion engine technologies necessitates not only design enhancements but also the exploration of alternative fuels or fuel catalysts. These endeavors are integral to curbing the emission of hazardous substances in exhaust gases. Most contemporary catalyst additives are of complex chemical origins, introduced into the fuel during the fuel preparation stage. Nonetheless, none of these additives yield a significant reduction in fuel consumption. The research endeavors to develop the fuel system of a primary marine diesel engine to facilitate the incorporation of pure hydrogen additives into diesel fuel. Notably, this study introduces a pioneering approach, employing compressed gaseous hydrogen up to 5 MPa as an additive to the principal diesel fuel. This method obviates the need for extensive modifications to the ship engine fuel equipment and is adaptable to modern marine power plants. With the introduction of modest quantities of hydrogen into the primary fuel, observable shifts in the behavior of the fuel equipment become apparent, aligning with the calculations outlined in the methodology. The innovative outcomes of the experimental study affirm that the mass consumption of hydrogen is contingent upon the hydrogen supply pressure, the settings of the fuel equipment, and the structural attributes of the fuel delivery system. The modulation of engine load exerts a particularly pronounced influence on the mass admixture of hydrogen. The proportion of mass addition of hydrogen in relation to the pressure of supply (ranging from 4–12 MPa) adheres to a geometric progression (within the range of 0.04–0.1%). The application of this technology allows for a reduction in the specific fuel consumption of the engine by 2–5%, contingent upon the type of fuel system in use, and concurrently permits an augmentation in engine power by up to 5%. The resultant economic benefits are estimated at 1.5–4.2% of the total fuel expenses. This technology is applicable across marine, automotive, tractor, and stationary diesel engines. Its implementation necessitates no intricate modifications to the engine design, and its utilization demands no specialized skills. It is worth noting that, in addition to hydrogen, other combustible gases can be employed.

**Keywords:** hydrogen; additives; internal combustion engine; fuel catalysts.

## 1. INTRODUCTION

Practically a third of all fuel oil consumption is referred to as transport energetics. So, the problem of fuel and energy resources usage is very urgent today in the world [1, 2] as a whole, in stationery [3, 4] and transport [5, 6] energetics, in particular, combustion engines of all types: internal combustion engines [7, 8], gas turbines [9, 10] and engines [11, 12]. The latter made a great impulse to further develop the general trend in enhancing the fuel efficiency of combustion engines as driving engines in integrated energy plants (IEP) [13, 14] for combined cooling, heat, and power (CCHP) generation, or tri-generation [15, 16]. In turn, the general tendency in solving this problem is associated with enhancing the combustion processes accompanied by adequate engine de-signing, the thermodynamic efficiency of the engine cycle through improving the working fluid (air and fuel mixture) parameters and exhaust heat utilization by applying advanced and modified waste heat recovery and ecology saving [17, 18] circuits with high efficient heat recuperating and exchanging apparatuses [19, 20] and circulation devices [21, 22]. At the same time, there are a large number of ways to increase the efficiency of fuel consumption by internal combustion engines. But most of them are quite complex, requiring significant changes in the design or the use of expensive catalytic additives. In this work, it is proposed to reduce fuel consumption and ensure an increase in engine power due to minor changes in the design of the fuel equipment of diesel engines and the use of gaseous hydrogen. This will have a positive effect on the economic, ecological, and, at the same time, logistics parameters of freight transportation and the state of stationary energy, where these types of power plants are used.

## 2. FUEL COMBUSTION WITH HYDROGEN ADDITIVES

In reality, modern combustion engines are of cogenerative or trigeneration types desired to convert the exhaust heat to steam and hot water (cogeneration) or refrigeration (trigeneration) [21, 22]. When the latter is used for conditioning (cooling) engine sucked air or scavenge air, we deal with the so-called in-cycle tri-generation [23, 24]. Such air conditioning systems

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(ACS) of energetic application as waste heat recovery systems (WHRS) [25, 26] gained a widespread application in stationery and ship power plants. Their cooling potential depends on the depth of engine exhaust heat utilization: the deeper the exhaust heat utilization, the higher the refrigeration potential of WHRS. The hybrid waste heat recovery systems are developed for engine deep intake air cooling [27,28] through heat transfer intensification [29, 30] and by application of engine cyclic air cooling and coolant [31, 32] as chilled water and refrigerant re-circulation contours providing maximum heat flux [33, 34] due to incomplete phase change [35, 36].

The other general trend in fuel saving is associated with the application of alternative fuels [37, 38] and additives to heavy viscosity fuels to increase fossil fuel saving [39, 40] and environmentally friendly engine operation efficiency [41, 42]. It should be pointed out that practically most of the engine exhaust heat utilization [43,44] and waste heat conversion [45,46] technologies as well as all the principal methodological findings in system designing [47,48], in particular rational load distribution [49, 50], might be successfully used for stationary [51, 52] and transport [53, 54] application.

The limited reserves of fossil resources underscore the significant attention directed toward exploring the potential for alternative fuels in transportation systems. Diesel and spark-ignition internal combustion engines (ICE) are anticipated to be prominent engine types for small and medium-sized transport applications in the coming decades. Consequently, the principal challenge in advancing transportation energy solutions lies in ensuring the efficient operation of engines using alternative fuels [55].

Various types of alternative fuels can be employed in internal combustion engines: ethyl and methyl alcohols [56], vegetable oils (such as palm, soybean, sunflower, and rapeseed) [57], natural and associated gases, as well as gas condensate [58], hydrogen [59, 60], and synthesis gas, predominantly comprising 40-70% hydrogen and carbon monoxide [61].

Undoubtedly, hydrogen stands out as the most promising among alternative fuels [62]. Humanity possesses boundless reserves of this fundamental element, the first in the periodic table. The transition of reciprocating engines to hydrogen represents a viable pathway to mitigate the greenhouse effect and address the issue of air pollution on our planet [63, 64].

Physicomechanical and physicochemical methods, along with their associated equipment, are widely used in purifying exhaust gases from contaminants and harmful impurities [65, 66].

The growing interest in alternative fuels research is primarily attributed to two key factors:

- The swift depletion of explored oil reserves, stemming from the heightened consumption of hydrocarbons.
- The worsening environmental condition due to the ongoing proliferation of reciprocating engines worldwide.

Figure 1 illustrates the trend in global oil price escalation over 15 years [67].

The use of hydrogen as a fuel for ICE is a complex problem that includes a wide range of issues:

- The possibility of transfer to the hydrogen of modern engines.
- The investigation of the operational processes of hydrogen-powered engines.
- The determination of optimal methods for controlling engine operation to minimize toxicity and maximize fuel efficiency.
- The design of a fuel delivery system to facilitate the efficient operation of cylinders in the ICE.
- The development of effective onboard hydrogen storage methods for transportation.

Numerous studies have focused on incorporating hydrogen into primary fuel. For example, H. Koten's work demonstrates that introducing hydrogen through the intake manifold at flow rates between 0.2 to 0.8 l/min enhances both technical and environmental performance, but only in small quantities [68,69]. W. Tutak [12] examines the impact of hydrogen addition to a dual-fuel diesel marine engine operating on natural gas. Results suggest that only modest amounts of hydrogen positively influence the operational process, while an increase in hydrogen content exceeding 10% leads to adverse consequences. Similar findings are reported by other authors [70].

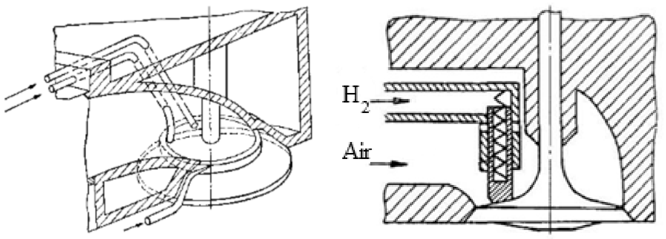
However, despite the appeal of hydrogen as a fuel, its drawbacks should not be overlooked. It is worth noting that the production of hydrogen remains a challenging task, requiring further investigation [71]. Issues related to the utilization of


**Fig. 1.** Dynamics of rising oil prices in the world over 15 years

alternative fuels also include fuel storage and supply to the combustion chamber. The supply of hydrogen to the working cylinder is of particular interest, mainly due to a relatively low density of hydrogen and low ignition energy, which can lead to reverse flashes during intake.

In the case of hydrogen-containing fuels in diesel engines, both internal and external mixture formation methods can be employed. External mixing, due to the relative simplicity of the engine fuel delivery system, is the most prevalent method of supply.

The most common method of gas supply in external mixing involves supplying a cyclic dose in the intake valve area of each cylinder separately. The analysis of the most common hydrogen supply schemes is provided in [72]. For instance, in Fig. 2, the gas supply is conducted through several tubes connected to the additional seat of the intake valve.




(a) (b)

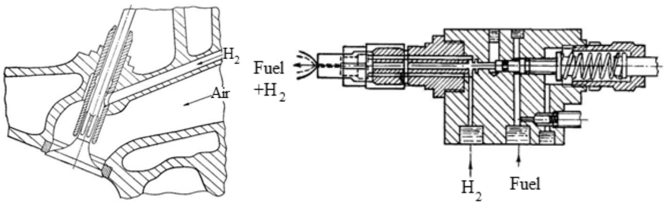
**Fig. 2.** Schematic diagrams of hydrogen supply through the intake valve seat (a) and of the spool mechanism of hydrogen supply (b)

When the valve is opened, the additional chamfer opens the holes and under the action of the discharge, hydrogen fuel enters the working cylinder.

In the gas supply schemes shown in Fig. 2a, [72] and Fig. 2b, [73], the hydrogen supply starts with some delay in opening the inlet valve and ends before the valve closes.

The feed time corresponds to approximately half the duration of the open state of the valve. The feed mechanism shown in Fig. 2b is a spool located in the inlet channel. When the inlet valve is opened, the supply of hydrogen is under a pressure of about 0.1 MPa.

In the gas supply configuration depicted in Fig. 3a, the function of the spool is assumed by the valve stem and guide. The stepped design of the valve and guide creates a cavity, allowing hydrogen to enter the inlet. In this setup, the hydrogen pressure within the system is maintained at 0.1 MPa.




(a) (b)

**Fig. 3.** Schematic diagram of hydrogen supply through the inlet valve guide (a) and of a hydrogen injector with a hydraulic drive of a single-cylinder engine SBY (b)

As mentioned earlier, a more promising approach is internal mixture formation, which involves directly supplying gas to the engine cylinder at the conclusion of the intake or compression phase. This method not only facilitates an increase in engine power but also eliminates the risk of flashbacks. However, this delivery scheme comes with certain drawbacks, including the challenge of providing a substantial quantity of hydrogen within a relatively brief time limit and issues related to the implementation of the supply system, hydrogen dosing, and other factors [73].

In Fig. 3b, a diagram is presented illustrating a hydrogen injector for the internal mixture formation in a single-cylinder engine SBY [74].

Burning fossil fuels causes serious environmental problems. Vehicle exhaust gases such as $NO_X$, CO, $CO_2$, and unburned hydrocarbons have a major negative impact on the environment [75].

Engine emission level is determined by engine operating conditions. Emissions from the main engine consist of nitrogen oxides, carbon oxides, and burnt hydrocarbons.

$NO_X$ – nitrogen oxides are usually formed at elevated temperatures.

CO and $CO_2$ are formed when fuel is burned. If there is enough oxygen, CO is oxidized to $CO_2$. Carbon monoxide is formed mainly with an over enriched mixture [75].

Unburned hydrocarbons arise from the incomplete combustion of fuel. Heat within the combustion chamber is dissipated to the chamber walls, preventing the combustible mixture along the walls from fully igniting. Moreover, the presence of gaps and crevices in the combustion chamber hinders the propagation of the flame, thereby elevating the concentration of unburned hydrocarbons. When the combustion rate is excessively low, unburned hydrocarbons are expelled through the open exhaust valve. Achieving complete fuel combustion necessitates an increase in the combustion rate, a task that can be accomplished by introducing additional hydrogen into the combustible mixture [76].

Hydrogen is released as an additional fuel. When it is used, the fuel burns better, the burning rate is higher, and the exhaust gases are cleaner. The flame propagation speed of hydrogen is higher than that of the second fuel, and therefore potentially less heat is released into the environment. This improves thermal efficiency.

Hydrogen can serve as an additive in gasoline, diesel, and natural gas engines. There are various methods for supplying hydrogen. In the conducted research, hydrogen was generated by a hydrogen generator or introduced with an air charge [77].

The addition of hydrogen enables the engine to operate on a cleaner mixture, resulting in reduced fuel consumption and diminished carbon dioxide emissions. Incomplete combustion is a primary cause of CO, HC, and NOX emissions in gasoline and diesel engines. Enhancing the completeness of fuel combustion leads to reduced pollution levels [78].

A proposed solution to this problem involves introducing small impurities of hydrogen (0.2–1.0% by weight) into the primary liquid fuel of the internal combustion engine. It is important to note that, in this context, hydrogen does not replace hydrocarbon fuel as an energy source; instead, it functions as a catalyst for fuel combustion within the engine cylinders.

The assertion that hydrogen acts as a catalyst in the combustion process is substantiated by the fact that even in small quantities, despite its high calorific value (Qn = 120 MJ/(kgK)), it does not significantly alter combustion as an additional fuel. However, the presence of hydrogen in the cylinder serves to stimulate the combustion process and functions as a catalyst [79].

Research conducted in the laboratory of advanced energy technologies revealed that small hydrogen impurities in the primary liquid diesel fuel of internal combustion engines enhanced the combustion of diesel fuel, especially with heavier grades. This shifts the internal combustion engine towards a constant volume combustion process and results in a redistribution of the engine heat balance, reducing the proportion of the heat released into the environment through the cooling system and exhaust gases.

Consequently, there is an increase in engine efficiency, ranging from 0.5% to 5.0%, depending on the quantity of hydrogen impurities and the engine load. These findings are consistent with the results obtained by other researchers.

Previous research has indicated that even minimal amounts of hydrogen impurities positively impact internal combustion engine performance, especially during partial and transient operational modes, particularly when using heavier grades of standard diesel fuel. This effect is most pronounced in such situations.

However, it is crucial to note that the results obtained in these studies are qualitative and do not provide a basis for developing precise methods to quantify processes involving hydrogen impurities. Therefore, they do not offer a definitive determination of the optimal quantity of hydrogen to be introduced into the cylinders of diesel internal combustion engines. Practical recommendations for modernizing internal combustion engines using such impurities are also currently unavailable.

A significant factor affecting the efficiency of hydrogen impurities is the method of feeding them into the internal combustion engine. While adding hydrogen to the engine intake is a simple approach, it complicates the quality control of the internal combustion engine and poses safety concerns due to the potential formation of an explosive mixture in the intake tract, leading to ignition and explosion. Such incidents were observed in both Otto-cycle internal combustion engines and diesel engines.

One possible solution is the supply of small hydrogen impurities using the method proposed by the research team led by Prof. N.N. Patrakhaltsev [79]. The main idea involves adding hydrogen to diesel fuel in the high-pressure line at low pressure with a special device. During a pressure wave, diesel fuel becomes saturated with hydrogen, enters the injector, and is then injected into the engine cylinder. After injection and pressure reduction in the cylinder, hydrogen is released from diesel fuel, promoting further droplet grinding and quick diffusion into the piston space. The amount of hydrogen added to the cyclic supply of diesel fuel is regulated by the hydrogen pressure at the device inlet. The term "hydrogen additives" refers to adding a portion of hydrogen not exceeding 0.1% by mass of the primary fuel supply. However, insufficient information was found in the scientific literature on the results of an experimental study of the addition of hydrogen to the main liquid fuel of the internal combustion engine. Therefore, the task of the study was the experimental confirmation of this theory and obtaining qualitative results.

The main aim of this research is to obtain data from fuel system experimental standby:

- To obtain data on the operation of the engine on diesel fuel with and without the use of small hydrogen impurities to check the adequacy of the mathematical model of the operating cycle of a diesel engine.
- To develop an experimental stand that will allow changing the main parameters of the fuel system of an engine operating with the use of small admixtures of hydrogen to the main fuel, and to determine the effect of hydrogen on atomization characteristics and effective engine performance.
- To derive the calculated dependencies for hydrogen concentration in the fuel and the saturation parameters of diesel fuel with hydrogen for the investigated engine based on its load characteristic.

## 3. MATERIALS AND METHODS

### 3.1. Experimental research

#### 3.1.1. Experiment for small impurities of hydrogen in an IC engine

An electronic automated test rig is required to investigate fuel equipment, particularly for introducing minute hydrogen impurities into the high-pressure fuel line.

In contemporary high-speed diesel engines, the fuel delivery process lasts only 1–4 milliseconds, especially when the pump plunger operates at high speed. The compression and fuel injection processes exhibit a pulsed and non-stationary nature. Fuel, being an elastic medium, transmits pressure at the speed of sound, ranging from 1200 to 1600 meters per second. Even the slightest variation in volume within a fluid-filled hydraulic system results in a rapid change in pressure.

Pressure pulses, originating from a perturbation source, encounter obstructions at the system endpoints, resulting in partial reflections that generate both return and total waves. These waves significantly distort the injection characteristics. Towards the end of the fuel delivery cycle, pressure waves reflected from the closed discharge valve can lead to subsequent needle movements following the primary injection period. These unintended "injections" are undesirable as they exhibit lower injection pressure, resulting in coarser and uneven fuel spray patterns. This, in turn, leads to increased smoke production, heightened soot formation, elevated specific fuel consumption, and conditions conducive to coking within the injector spray orifices.

As fuel delivery nears its conclusion, the motion and reflection of waves within the high-pressure chamber (pump assembly - discharge line - injector) gradually diminish due to the irreversible dissipation of energy caused by friction. This process eventually stabilizes at a residual pressure. Typically, the longer the fuel line and the higher the frequency of injection pulses, the more pronounced the impact of wave phenomena on fuel delivery characteristics. This factor exerts a lesser influence on pump injectors, where the discharge line is absent, and the wave effect is minimal.

For a comprehensive exploration of these processes, an experimental installation known as DVZ-1-MDV, based on the fuel system of the D65 diesel engine (4Ch11/13), was conceived and developed. The schematic layout of this experimental setup is presented in Fig. 4, with accompanying photos in Fig. 5. The experimental setup consists of three subsystems:

- A subsystem (based on the fuel system of the D65 engine) to study the parameters of fuel injection with the addition of hydrogen gas.
- A measurement subsystem (Fig. 4).
- A subsystem of automation and regulation.

As a basis of research, the turbo piston diesel internal combustion engine injection process works with the addition of hydrogen on a pressure drop wave in the fuel line of high pressure, the stand based on the fuel system of the diesel 4Ch11/13 working from the three-phase electric motor was developed.

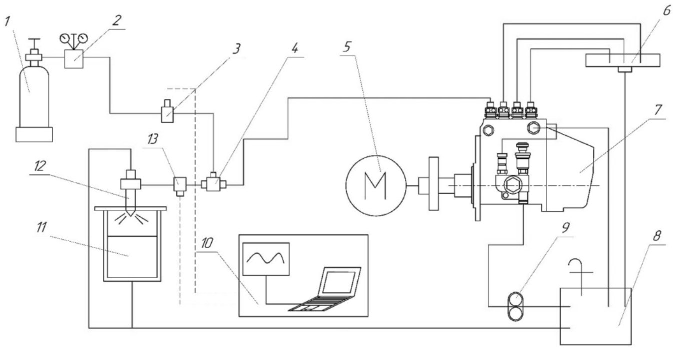



**Fig. 4.** Installation scheme: 1 – hydrogen cylinder; 2 – industrial hydrogen reducer; 3 – pressure sensor; 4 – hydrogen addition valve; 5 – electric motor; 6 – fuel discharge capacity; 7 – HPFP; 8 – expenditure tank; 9 – fuel pump; 10 – computer system for measuring and processing data; 11 – injection tank; 12 – nozzle; 13 – pressure sensor

To lay the groundwork for the research, a test stand was developed based on the fuel system of the 4Ch11/13 diesel engine, which operates with a turbo-piston diesel internal combustion engine. This setup involves injecting hydrogen within a pressure drop wave in the high-pressure fuel line and is powered by a three-phase electric motor.

Hydrogen from the 5-liter volume cylinder 1 enters the additive injection valve 4 through gearbox 2. Valve 4 is installed in front of the fitting of the standard nozzle 12, mounted on the rod, and placed in the spray bottle 11. The high-pressure fuel pump is operated by a three-phase AC motor 5, connected via a coupling, and controlled by a frequency converter to regulate the shaft speed.

A digital tachometer is installed on the coupling of the high-pressure fuel pump (HPFP) and the electric motor. Fuel consumption through the HPFP is measured in a measuring glass 11. To register hydrogen pressure, the strain-electric pressure sensor "OVEN PD100-DI6,0" 3 is used.

The pressure in the fuel line is converted into a current signal by a dynamic fiber-optic pressure sensor for high-temperature pressure measurements, "OPTRAND AutoPSI-S2000" (Fig. 5) 13, with an upper measurement limit of 200 MPa and an output signal of 0.5–5 V. This allows for a qualitative assessment of fuel pressure and investigation of processes in the high-pressure pipeline.

**Fig. 5.** Dynamic pressure sensor Optrand AutoPSI-S2000

The signals of the primary sensors from the stand DVZ-1-MDV are received electronically to the USB-oscilloscope and the computer system for measuring and recording data "IRIS" 10. The installation of the sensor "Optrand AutoPSI-S2000" in the high-pressure line is shown in Fig. 8.

After setting up the experimental stand, corresponding experimental data regarding the capability of the technology and further exploration of the specified processes were obtained. The variation in load occurred step by step through the incremental connection of heating elements (TENs). During hydrogen pressure measurements, the pressure was maintained at 10 MPa. Figure 6 illustrates the change in the amount of hydrogen admixture (by mass) depending on the generator load at a pressure of 10 MPa. The data were obtained experimentally with a stepwise increase in load by 1 kW.

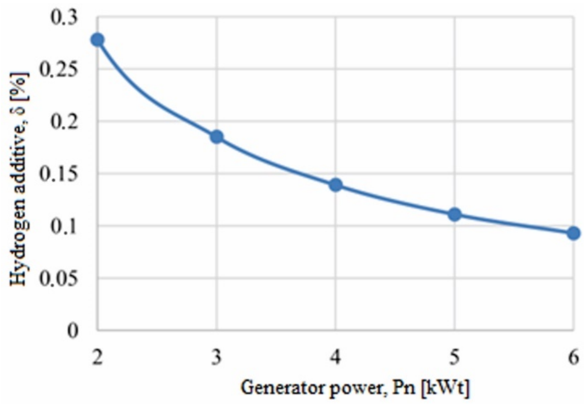



**Fig. 6.** Dependence of hydrogen mass impurity on engine load at a pressure of 1.0 MPa

Figure 7 presents an experimental investigation according to the generator load characteristic, comparing the engine operation with and without the hydrogen additive. The data were collected corresponding to an increase in the generator load. The obtained values at specific points of the characteristic were systematized along the trend line. Thus, corresponding dependency graphs were obtained.

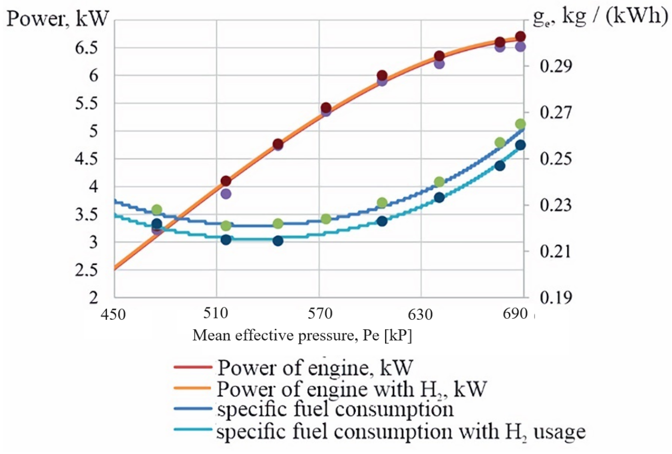



**Fig. 7.** Comparative performance of the engine 1Ch8.6/7.2 working with small impurities of hydrogen and "pure" fuel

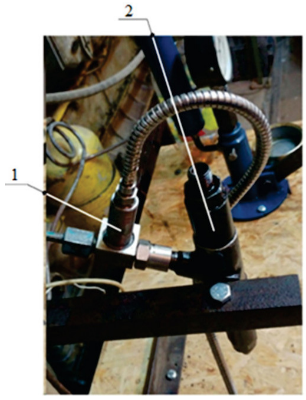


**Fig. 8.** Installation of the sensor "Optrand AutoPSI-S2000" in the high-pressure line: 1 – pressure sensor; 2 – nozzle

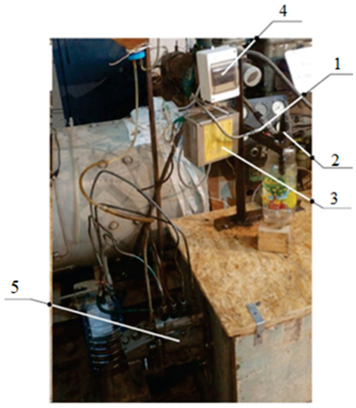


**Fig. 9.** Experimental installation based on the fuel equipment of the engine 4CH11/13: 1 – pressure sensor; 2 – nozzle; 3 – the block filter of a signal; 4 – the power supply unit of pressure sensors "OVEN"; 5 – high-pressure fuel pump

#### 3.1.2. Parameters of fuel equipment with the addition of h2 small impurities

Investigations of the 4CH11/13 engine fuel equipment parameters with hydrogen addition to the diesel fuel were conducted to study the effect of small hydrogen impurities addition to diesel fuel on the processes in the high-pressure fuel line Fig. 9. During the tests, the spring of the injector needle had a serial tightening $P_{\text{in}} = 17.6$ MPa.

The research program included:

- A study on some changes in fuel system parameters and their optimization when the hydrogen addition is in use.
- A study on the effect of hydrogen additive usage on the process of diesel cylinder mixture formation.
- An assessment of the additive impact on the economic and environmental performance of the diesel engine and the choice of the additive amount.

The process of fuel supply, both with and without additives, is conducted in a truly brief period, with minor changes in the basic parameters of fuel supply significantly affecting the performance of the diesel process. When adding hydrogen, it is possible to expect changes in the basic parameters of the fuel supply. Table 1 shows the characteristics of the experimental stand DVZ-1-MDV measuring equipment.

### 3.2. Processing of experiment results

Understanding the impact of hydrogen additives on fuel supply parameters and subsequent regulation within the fuel delivery system can help mitigate alterations. Conducting comparative tests to ensure that primary fuel supply parameters remain consistent, both with and without additives, allows for the inference that any variations in working process characteristics are solely attributable to the in-cylinder influence of hydrogen on diesel fuel combustion. The results obtained through a USB oscilloscope were transferred into a software environment and are presented in the format depicted in Fig. 10.

During the study, hydrogen pressure changed according to its flow rate from the storage chamber (Fig. 11). A significant effect on the maximum injection pressure was observed with increasing hydrogen supply pressure.

The presence of hydrogen impurities at a pressure of 2.0 MPa leads to a decrease in maximum injection pressure by 5–8% with the serial injector spring tightening. Increasing the hydrogen supply pressure to 3.0 MPa reduces the maximum injection pressure by 15–18%. When the hydrogen supply pressure increases to 4.5 MPa, the maximum injection pressure decreases by 18–25% (Fig. 12). This result can be explained by the pressure loss during hydrogen gas compression and the "smoothing"

**Table 1**
Characteristics of the experimental stand DVZ-1-MDV measuring equipment

| Name of measuring instrument, equipment | Brand | Measurement limits | Measurement error |
|---|---|---|---|
| Tachometer | Pennant | 600...8000 min$^{-1}$ | ±1% |
| Dynamic pressure sensor | Optrand AutoPSI-S2000 | 0...200 MPa | ±0.5% |
| Pressure sensor | "OVEN PD100-DI6,0" | 1.0...6.0 MPa | ±0.5% |
| Frequency meter | CH4-34A | 10 Hz...120 MHz | ±0.5% |

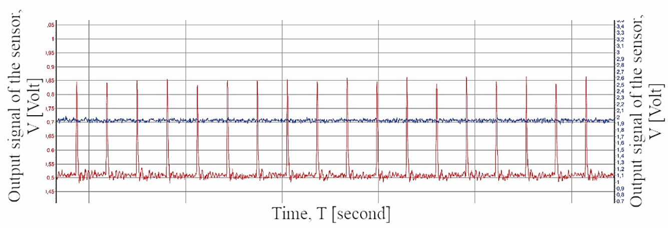



**Fig. 10.** Experimental diagrams of fuel injection and hydrogen supply pressure

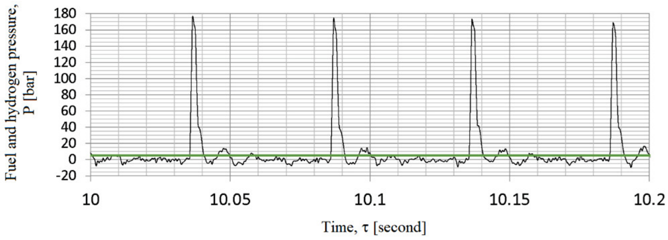



**Fig. 11.** Diagram of fuel injection without the addition of hydrogen

of wave oscillations in the high-pressure fuel line, along with the "softening" of the landing of the discharge valve. Further increases in hydrogen pressure do not significantly decrease the maximum injection pressure, which can be explained by the initial pressure increase in the fuel line due to excess hydrogen pressure.

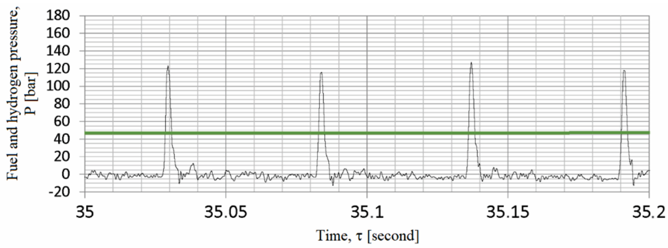



**Fig. 12.** Fuel injection diagram at hydrogen impurity pressure 4.5 MPa

In addition to changing the maximum injection pressure, the nature of the wave oscillations in the high-pressure fuel line changes. When the hydrogen supply pressure increases by more than 3.0 MPa (Fig. 13), the amplitude and frequency of oscillations decrease, and the fuel pressure diagram approaches the linear.

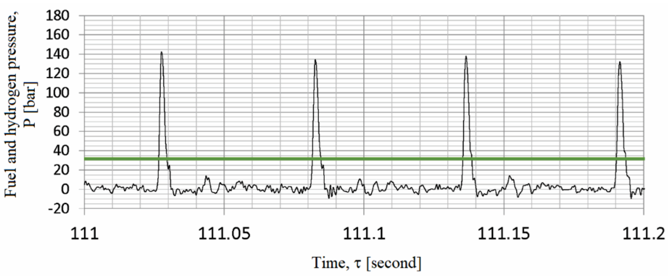



**Fig. 13.** Fuel injection diagram at hydrogen impurity pressure of 3.0 MPa

Figure 14 shows a fuel injection diagram at a hydrogen impurity pressure of 2.5 MPa.

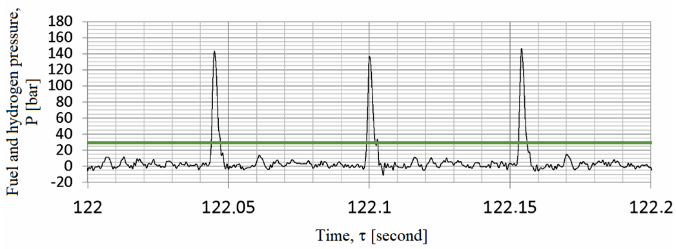



**Fig. 14.** Fuel injection diagram at hydrogen impurity pressure of 2.5 MPa

Figure 15 shows a fuel injection diagram at a hydrogen impurity pressure of 2.0 MPa.

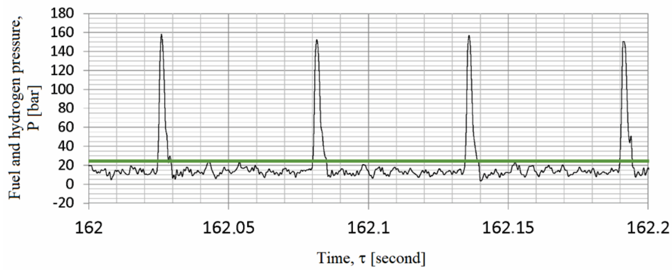



**Fig. 15.** Fuel injection diagram at hydrogen impurity pressure of 2.0 MPa

The influence on processes within the high-pressure fuel line can be attributed to the actions of hydrogen gas. As hydrogen enters the fuel line, it absorbs the pressure wave generated by the closure of the discharge valve, effectively acting as a damper to attenuate subsequent pressure fluctuations in the fuel line. Consequently, these pressure wave reductions make it possible to maintain an excess of hydrogen pressure, filling the "pressure drop zone" within the fuel line. The overall experimental relationship between the maximum change in fuel injection pressure and hydrogen additive pressure is illustrated in Fig. 16.

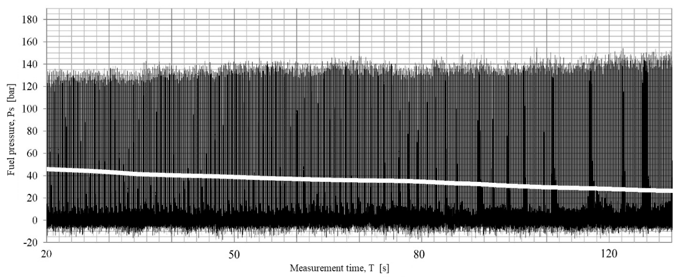



**Fig. 16.** Experimental dependence of the maximum fuel injection pressure changes by hydrogen additives pressure

The research results show (Fig. 17) that when comparing the injection diagrams in the needle landing area there are characteristic changes, namely:

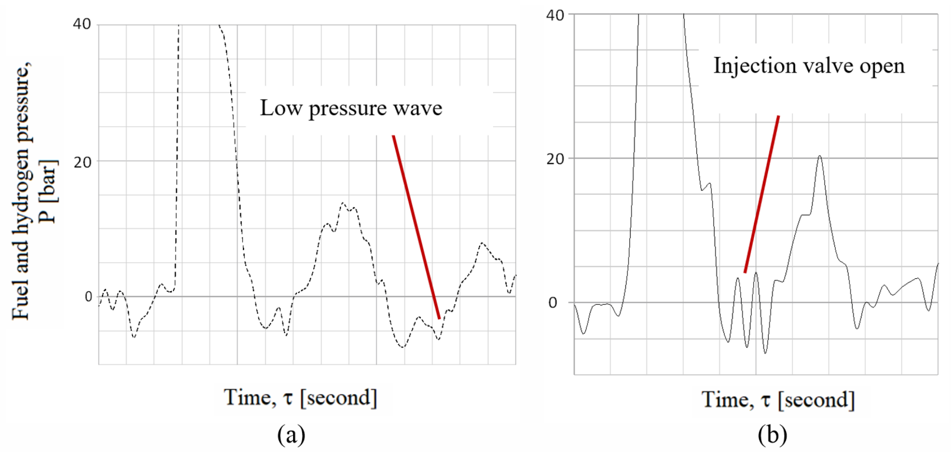



**Fig. 17.** Hydrogen pressure diagrams in a high-pressure fuel line: (a) without hydrogen; (b) with hydrogen

- No rarefaction waves in the diagram with the hydrogen addition.
- Dynamic oscillations in the fuel line due to the supply of hydrogen through the valve.

## 4. RESULTS AND DISCUSSION

### Mathematic modeling of gas diffusion in non-stationary liquid

Studies on gas diffusion into non-stationary liquids are of independent interest, as theoretical and experimental studies conducted in virtually stationary liquids provide valuable information about gas-liquid reactions. However, the starting point for models of the mixing fluids absorption process often involves cases with stationary liquids.

In the case of gas diffusion in non-stationary liquids, convective mixing of mass occurs, promoting the transfer of dissolved gas in the liquid stream. Let us simplify the assumption that the liquid has a free interface with the gas.

Assuming a smooth surface for this interface, as the surface tension forces for the macro-volume of the fluid exceed friction forces inside fluid flow, we can assume that the contact surface of the fluid is physically homogeneous and has a constant geometry. Given that the thickness of the interface is much less than the column of liquid, we can assume that the liquid has almost infinite depth. That is, during the analyzed time, the diffusion process does not lead to significant changes in gas concentration in the mass of liquid.

Suppose that some surface Ft is in contact with the gas at time $\tau = 0$, and from this moment the concentration of gas over the entire surface Ft is constant and equal to $C*$, and the flat field of concentrations $C(F)$ is homogeneous. The concentration of $C*$ corresponds to the solubility of the gas at its partial pressure above the liquid surface, $P_{\mathrm{H2}} = \mathrm{const}$ at $T = \mathrm{const}$. Further, if the solubility of the gas is not extremely high, i.e. the concentration expressed in mole fractions is much below one, it can be assumed that the dissolved gas diffusion into the liquid does not significantly affect its temperature and other physical properties.

Under the accepted conditions of change in time and space, the dissolved gas concentration in diesel fuel can be described by the following diffusion equation [80]:

$$D_c = \frac{\delta^2 C}{\delta x^2} = \frac{\delta c}{\delta \tau},$$

where: $x$ – the distance measured into the depth of the liquid, $D_c$ – the diffusion coefficient of the gas in the liquid.

To calculate the amount of gas $Qc$ absorbed by the fuel between the two injections, this time interval $t$ is divided into three stages. The first $t_1$ - oscillating movements in the pipeline after injection, during this time there will be $K$ oscillations, and their amplitude will decrease to zero. The second $t_2$ is the stage of oscillations absence in the pipeline and, finally, the third stage is the injection itself. Therefore, the amount of gas q absorbed by the unit of the phase interface will also consist of three terms $q_1$, $q_2$, and $q_3$.

In the case of a non-stationary liquid, the formula for calculating $q$ is as follows [81]:

$$q_\tau = 2\left(C^* - C^o\right)\sqrt{\frac{D_c \tau}{\pi}},$$

where: $C^o$ – the initial gas concentration in the fuel [kg/cm$^3$], $D_C$ – diffusion coefficient [cm$^2$/sec], $C*$ – the maximum possible concentration at $P--T$ [kg/cm$^3$] and is determined from Henry's law:

$$C^* = P\frac{1}{\mathrm{He}}.$$

Henry's coefficient He depends only on temperature, increasing with increasing the latter.

The He temperature dependence for binary solutions can be obtained from the equation of equilibrium between phases during physical absorption proposed by Krichevsky [82]:

$$\mathrm{He} = 524395^{\exp(-F/RT)},$$

where: $F$ – the differential heat of dissolution [kJ/kmol].

The equation is used to determine $D_C$:

$$D_c = 7.41^{-8}\frac{E(\lambda M)^{0.5}}{\mu V^{0.6}},$$

where: $M$ – the molecular weight of the solvent, $T$ – temperature [K], $\mu$ – the viscosity of the solvent, $\nu$ – the volume of 1 mol of solute at normal boiling point [cm$^3$/mol], $\lambda$ – the correction factor.

As a result of calculated studies (Figs. 18 and 19) of gas absorption of diesel fuel, because the heat of evaporation of diesel fuel in the cylinder ranges from 26 300 to 34 000 kJ/mol and has the same order as the activation energy required to saturate diesel fuel gas $E = 28\,000 \pm 1200$ kJ/mol and $18\,100 \pm 1100$ kJ/kmol, it can be assumed that the dissolved gas in a drop of diesel fuel will be desorbed when heat is supplied to the drop together with the evaporating molecule.

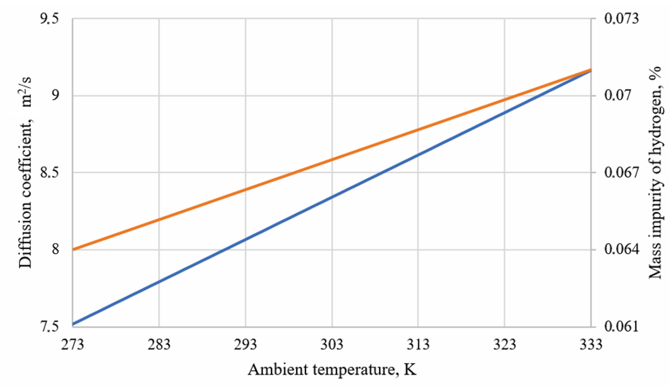



**Fig. 18.** Dependence of the diffusion rate $D_C$ and mass impurity of hydrogen $\Delta H_2$ on the solvent temperature

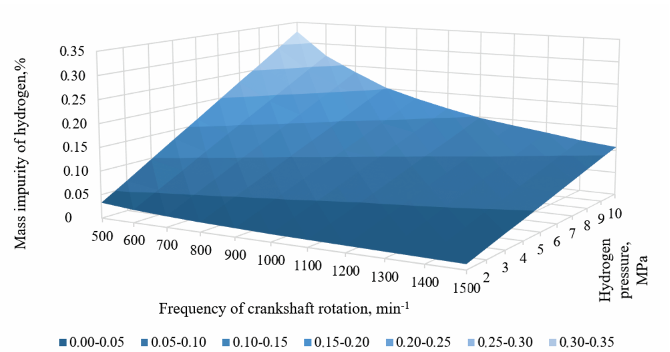



**Fig. 19.** Dependence of hydrogen mass impurity on crankshaft speed and hydrogen supply pressure

## 5. CONCLUSIONS

1. Initial data on the diesel engine operation with and without the use of small hydrogen admixtures were obtained for the first time. This was achieved by introducing hydrogen during the rarefaction wave in the high-pressure fuel line.
2. An experimental setup was developed to observe changes in the main parameters of the engine working cycle when operating with small hydrogen admixtures alongside the primary fuel. This will enable the determination of hydrogen influence on fuel atomization characteristics and engine performance.
3. It was experimentally established for the first time that when using small hydrogen admixtures in diesel engines:
   (a) The mass fraction of hydrogen introduced into the engine is most influenced by hydrogen pressure, engine load, and geometric parameters of the high-pressure fuel line.
   (b) Depending on the factors mentioned above, experimental values were obtained, indicating that the mass of hydrogen admixture varies from 0.05 to 0.25%.
4. The methodology for calculating hydrogen absorption processes in diesel fuel was improved. This allows for a qualitative assessment of hydrogen solubility under the conditions of the diesel engine fuel apparatus.
5. Based on preliminary experimental data, fuel savings with the application of this hydrogen delivery method are estimated to be in the range of 1.7–5.2%.
6. This technology can be used in marine, automobile, tractor, and stationary diesel engines. Its implementation does not require complex conversion of the engine design, and its application does not require exceptional skills. In addition to hydrogen, other combustible gases can be used. With minor modifications, this technology can be implemented in gasoline engines of the TFSI type in which virion injection occurs inside the cylinder and there is also an environment with variable pressure in the fuel line. Therefore, this technology has a wide range of applications in several types of engines and leads to an increase in the economic and operational performance of vehicles.

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