

AN OUTLOOK OF HYDROGEN AS AN AUTOMOTIVE FUEL

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Abstract—The characteristics of the use of hydrogen as an internal combustion engine fuel, of the metal hydrides for hydrogen storage and of hydrogen fuel feed systems for the cases of hydrogen as a primary fuel and as supplemental fuel. The results clearly establish that supplemental hydrogen in the gasoline-air mixture can (1) expand the range of combustibility of the fuel-air mixture and hence more lean, (2) increase the effective efficiency of the engine and (3) reduce toxic emissions.

1. INTRODUCTION

Supplying a certain amount of water to the fuel-air mixture improves the performance of Internal Combustion Engines (ICE) but its use cannot bring about the great energy-ecological benefits achieved by using hydrogen as a fuel or as an additive to fuels of petroleum origin. We look forward to using hydrogen as an ICE fuel for several reasons. While conventional energy sources such as coal, oil, and natural gas are nonrenewable, hydrogen can be coupled to renewable energy sources.

Hydrogen is the lightest element in the universe and was initially identified in the 18th century. Although it does not exist in a free state as a gas in nature, it is one of the most widespread elements and is found in many compounds. Hydrogen is easily obtained by a great number of processes, the simplest of which is water decomposition through electrolysis as a result of which hydrogen and oxygen are obtained in their gaseous states. The fact that hydrogen is an ideal fuel from the point of conservation of the environment is extremely important. The only toxic products of combustion of hydrogen are nitric oxides.

The use of hydrogen as a fuel for internal combustion engines is not novel. As early as the middle of last century, a hydrogen piston engine was designed. During the Second World War while Leningrad was besieged, some ordinary automobile engines were modified to burn hydrogen instead of gasoline.

The main problems of mass production of hydrogen as a basic fuel are storage as well as organizing a large scale system for the production and distribution of hydrogen. The systems developed for storing hydrogen in the automobile must be compared on an energy density, mass and price basis to the conventional liquid fuel

storage tanks. Potentially, gasoline has 900 Wh l^{-1} and while hydrogen has only 3 Wh l^{-1} [1].

The maximum range of travel with a single filling of fuel is an important parameter to estimate the relative mass of various fuels for an automobile. In Fig. 1 one can compare the maximum travel range of six systems having equal masses of the fuel systems.

2. HYDROGEN AS A FUEL FOR INTERNAL COMBUSTION ENGINES

The properties of hydrogen as a chemical element are well known. At normal temperature it is a colorless, odorless, nontoxic gas. At a temperature of 20 K hydrogen condenses and at a temperature of 14 K it passes into a solid state. Gaseous hydrogen is characterized by its high diffusion ability and the hydrogen diffusion coefficient in air is approximately three times as large as either the diffusion coefficient of methane, oxygen or carbon dioxide. Hydrogen is characterized by having the highest energy-mass coefficient of the chemical fuels and in terms of mass energy consumption it excels the conventional hydrocarbon fuels by about three times, alcohol 5 to 6 times, ammonium 7 times, etc. [2].

The basic properties of hydrogen and gasoline are shown in Table 1. The speed of flame spreading in the hydrogen-air mixture is about 265 to 325 cm s^{-1} [3-4] and it depends on the temperature of the mixture and increases with an increase of temperature.

The low activation energy of hydrogen a wide range of combustibility of the hydrogen-air mixture and the high speed of spreading of the flame create favorable conditions for the origin of an uncontrollable combustion process with abrupt increase of the pressure in the

Table 1. Physico-chemical properties of hydrogen and gasoline

No.	Property	Hydrogen		Gasoline
		gaseous	liquid	
1.	Molecule mass	2.016	2.016	107.0
2.	Density, g cm ⁻³ (20°C, 760 mm Hg)	83.764×10 ⁻⁶	0.0708	0.70-0.75
3.	Specific heat absorption J g ⁻¹ K	14.89	9.69	2.20
4.	Dynamic viscosity, g cm ⁻¹ s	0.0000875	0.000133	0.002
5.	Heat conduction, mW cm ⁻¹ K	1.987	1.00	1.31
6.	Range of combustion in air in volume, %	4-75	—	1.0-7.6
7.	Stoichiometric content in volume, %	29.63	—	1.76
8.	Minimum ignition energy in air, mJ	0.02	—	0.24
9.	Self-ignition temperature, K	858	—	501-744
10.	Flame temperature in air, K	2318	—	2470
11.	Amount of heat energy in percentage emitted by the flame in environment	17-25	—	30-43
12.	Combustion speed in air at normal conditions, cm s ⁻¹	265-325	—	37-43
13.	Detonation rate in air at normal conditions, km s ⁻¹	1.48-2.15	—	1.4-1.7
14.	Diffusion coefficient in air at normal conditions, cm ² s ⁻¹	0.61	—	0.05
15.	Rate of diffusion in air at normal conditions, cm s ⁻¹	2.00	—	0.17
16.	Rate of rise in air at normal conditions, m s ⁻¹	1.2-9	—	unrising
17.	Working mixture content-ra- tio of amount of air and fuel (a) ratio of air and fuel (in units of weight) (b) ratio of air and fuel (in unit of volume)	364.8-4.8 24-03	— —	25-4.3 100-16.7
18.	Theoretical content of the working mixture (a) ratio of air and fuel (in units of weight) (b) ratio of air and fuel (in units of volume)	34.3 2.38	— —	15.1 59.5
19.	Low heat of combustion (a) in mass kJ kg ⁻¹ (b) in volume kJ cm ⁻²	120,000 —	— 8,496	44,000 32,560
20.	Heat emission from 1 ml stoi- chiometric mixture, kJ (a) combustion products, mg; H ₂ O CO ₂ (b) change of the volume of exhaust gases	3.185 239.0 — -15%	— — — —	3.914 267.5 267.5 +5.5%

Table 1. Physico-chemical properties of hydrogen and gasoline (continued)

No.	Property	Hydrogen		Gasoline
		gaseous	liquid	
21.	Comparison of the volumes of hydrogen and its respective gasoline to obtain the same heat emission, liter			
	(a) at 20°C and 0.1 MPa	3,240	3,83	1
	(b) at 20°C and 20 MPa	16.2	—	1

cylinder, potentially producing shock waves and knocking, increase of heat emission in the walls and increase of mechanical losses [2]. Figure 2 shows comparative data of the speed of combustion of the gasoline-air mixture (continuous lines) and of the hydrogen-air mixture (dot lines).

The rate of the increase of the pressure of the engine cylinder burning hydrogen at stoichiometric content is nearly 3 times higher compared to gasoline. In lean mixtures it decreases.

The combustion power of the hydrogen-air mixture is lower than the combustion power of the gasoline-air mixture by about 10 times, and the temperature of the self-ignition of the hydrogen-air mixture depends on the mixture content and at stoichiometric content it is 858 K.

Figure 4 shows the dependence of the minimum combustion power of hydrogen and methane in air depending on the air to fuel ratio, a . The low combustion power in a wide range of change of a enables the engines burning hydrogen to change the air ratio from 4 to 5,

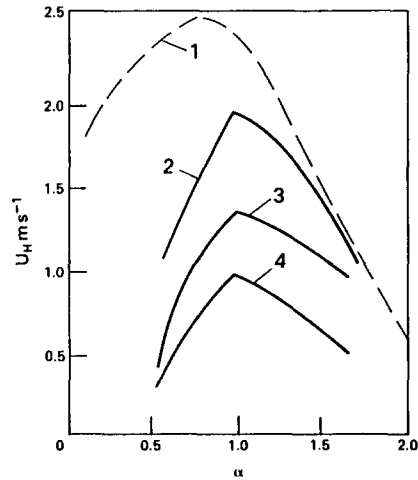


Fig. 2. Change of the normal flame spreading speed due to the content and temperature of the fuel-air mixture: 1 = 297 K; 2 = 473 K; 3 = 573 K; 4 = 673 K.

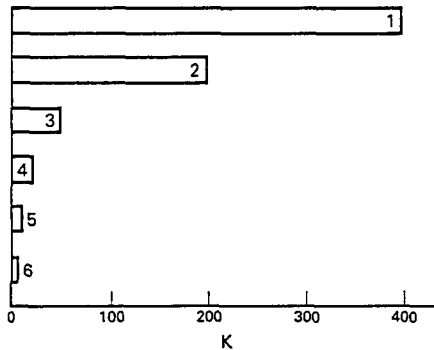


Fig. 1. Maximum course in km, travelled by a car with an equal mass (50 kg) of the fuel reservoirs and accumulators. 1 = work with gasoline; 2 = work with methanol; 3 = hydrogen, stored in a hydride reservoir at high temperatures; 4 = with hydrogen, stored in hydrides; 5 = an electric car with Na-S accumulators; 6 = an electric car with lead accumulators.

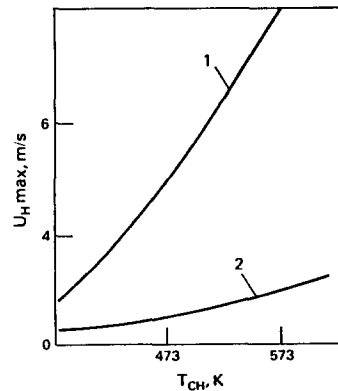


Fig. 3. Change of the maximum value of the normal flame spreading speed due to the temperature of the fuel-air mixture: 1 = hydrogen-air mixture; 2 = gasoline-air mixture.

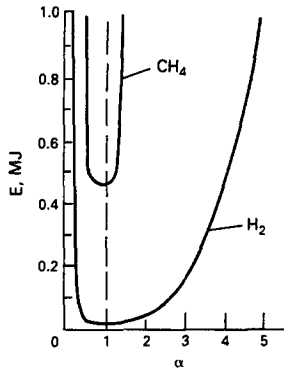


Fig. 4. Change of the minimum combustion power of hydrogen and methane in air depending on the air ratio.

while when working with gasoline α changes from 1.2 to 1.3.

When the engine works with hydrogen we have the following advantages: the hydrogen-air mixture has a wide range of combustibility and the speed of spreading flame front is high; hydrogen can easily mix with air and the hydrogen-air mixture is much more homogeneous than the liquid fuel-air. The formation of soot, hydrocarbons, carbon monoxide and the unpleasant odor of exhaust gases are absent. The hydrogen-air mixture is distributed in the cylinders much more uniformly. The cyclical fluctuations of the mixture content are lowered by a considerable extent, especially when accelerating and stopping the automobile due to considerably better mixture-formation of hydrogen and air.

Hydrogen offers the same advantages which the gaseous fossil fuels have. Unlike gasoline engines, engines burning hydrogen do not need enrichment when starting the engine, at idle or during acceleration, which hence leads to improvement of the engine economy. Since the range of hydrogen combustibility compared to gasoline is great, the air to fuel ratio varies from 0.13 to 10.2 which corresponds to a hydrogen content of 4 to 75 volume percentage in the hydrogen-air mixture [5]. Hence, an engine burning hydrogen will not need qualitative regulation of the mixture as is the case with diesel engines and the throttle valve can be eliminated. The removal of the throttle valve will bring about a reduction of mechanical losses at partial power settings and also an increase of efficiency. It is assumed that at partial power setting the power of the engine burning hydrogen and with qualitative regulation of the mixture is considerably lower compared to the gasoline engine with a throttle valve and the efficiency of the partial power setting grows from 20 to 50%. For example, at stoichiometric content of the mixture, gaseous hydrogen

fed together with air, occupies about 30% of the cylinder volume, while the gasoline mixture occupies only 2–4% and that brings about the lowering of the effective horsepower of the engine burning pure hydrogen with 20–25% [6].

Figure 5 shows schematically the maximum quantity of heat released in the engine cylinder with volume 1.0 at various ways of feeding hydrogen. Besides, one can see that when the engine burns gasoline, its vapor occupies about 17 cm³ of the cylinder, while hydrogen occupies volume in the cylinder of about 300 cm³. That can be explained by the small density of hydrogen and it is natural that the amount of air coming into the cylinder will be less and therefore the lowering of the space factor of the cylinder when burning hydrogen will bring about the lowering of the engine power.

The heat released from a unit of volume of stoichiometric mixture of hydrogen-air, obtained in the carburetor is almost 0.81 of the heat of stoichiometric mixture of gasoline-air. If hydrogen is directly fed into the engine cylinder, the heat released is about 20% greater [7]. From the data in Table 1 it follows that hydrogen density in a gaseous state is about 56 times smaller than the density of vaporized gasoline. Because of this the power factors of the engine burning hydrogen will depend on the manner of hydrogen feeding into the engine.

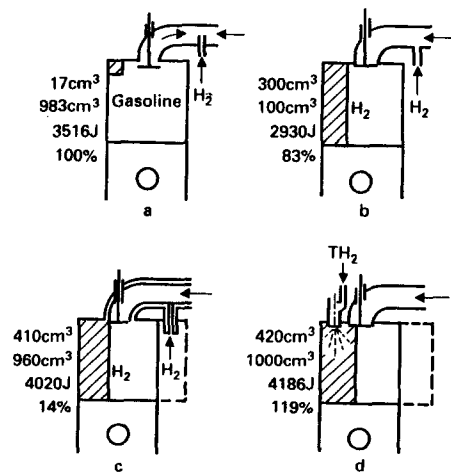


Fig. 5. Change of the maximum amount of heat released in the engine cylinder and of the volume occupied by gasoline and hydrogen according to hydrogen injection; a = engine burning gasoline; b = engine burning hydrogen and hydrogen injection into the engine intake manifold; c = engine burning hydrogen with liquid hydrogen injection into the engine intake manifold; d = engine burning hydrogen and liquid hydrogen injection into the cylinder space.

Backfiring can take place in the engine intake manifold due to the high reaction ability of hydrogen when the engine burns hydrogen. Greatest attention should be paid to flames occurring in the carburetor burning only hydrogen, a phenomenon observed by the first hydrogen engine researchers.

The tendency of flame appearance in the carburetor is explained by the low ignition energy of hydrogen. This deficiency can be eliminated by using lean fuel-air mixtures, recirculation of exhaust gases or water injection into the engine cylinders. These three methods bring about a lowering of the flame spreading rate and they increase the energy necessary to ignite the fuel-air mixture.

Taking other measures bringing about a lowering of the flame rate and energy can also be lower or eliminate the appearance of a flame in the carburetor. There will be no problems with the appearance of a flame in the carburetor if hydrogen is injected directly into the cylinders but the cost of the hydrogen injection system is much higher than that of the carburetor. That is why in almost all gasoline engines fuel is injected into the engine cylinders with the help of a carburetor and not by injectors.

Table 2 shows a comparison between the thermodynamic cycles of a hydrogen and a gasoline engine.

From the research on hydrogen engines with external and internal mixing, it follows that:

(1) When working with hydrogen and with cycle metering in the process of filling or condensing the work process of the engine is steady in a wide range of change of the air to fuel ratio, a . For continuous injection of hydrogen in the process of filling with values of 1 to 1.4,

the normal work of the engine is disturbed because of the appearance of backfiring as a result of premature combustion of hydrogen at the moment of its contact with the hot areas of the combustion chamber or with the residual gases in the cylinder space.

(2) When the mixture content is close to the stoichiometric content the working process of the engine burning hydrogen is characterized by forced work because of the high combustion rates of the hydrogen-air mixture.

(3) The engine power, when working with hydrogen and external mixing, is about 20–25% lower than the power when working with gasoline. With internal mixing the engine power is not lower, in fact it can even be raised.

(4) The optimum content at which maximum efficiency and minimum NO_x is achieved, is at $a = 5$ to 2.7.

(5) The effective factors of the engine are improved when hydrogen is added to the gasoline-air mixture up to 5–10%, the liquid fuel consumption goes down to 30–40% and the toxicity of the exhaust gases is considerably lowered.

Hydrogen can be stored in the automobile as a compressed gas, as a liquid in special containers at very low temperatures or in chemical compounds called hydrides. The small density of hydrogen is one of its basic deficiencies. At a pressure of 20 MPa and a temperature of 293 K, the density of gaseous hydrogen is five times less than that of liquid hydrogen and the necessary volume of the tank is 5.5 times greater than that of the liquid hydrogen. As gaseous hydrogen, related to volume, has very low energy density, in order to provide sufficient energy content, hydrogen can be

Table 2. Comparative characteristics of hydrogen and gasoline engines

Cycle	Hydrogen engine	Gasoline engine
Suction pressure, MPa	0.098	0.098
Pressure at the end of compression, MPa	1.355	1.624
Combustion pressure, MPa	6.215	8.079
Exhaust pressure, MPa	0.421	0.555
Suction temperature, K	300	333
Temperature at the end of compression, K	442	648
Combustion temperature, K	2288	3118
Exhaust temperature, K	1311	1882
Thermal efficiency	0.456	0.421
Work done by unit volume of working mixture, kJ m^{-3}	910	1320

stored under high pressure in containers. Calculations show that at comparative basis of equal energy content the tank under pressure should have 30 times greater mass and 24 times greater volume compared to the conventional gasoline tank [5].

The energy obtained from gasoline combustion from gasoline in the automobile tank can be obtained from 15 kg of hydrogen, while an ordinary steel container even under pressure of 15 MPa contains 630 g hydrogen in the gaseous state, which under normal conditions occupies a volume of 7 m³. The combustion heat of hydrogen contained in compressed state in a container with mass of 60 kg and volume 60 l does not exceed the combustion heat of 2.3 l of gasoline. Thus, from the mass of the containers one can easily estimate that the mass of the hydrogen tank will be about 2 metric tons.

In addition gaseous state hydrogen can be obtained and stored in the liquid state. Having in mind the liquid hydrogen density, the 15 kg of hydrogen, equal to the energy of one tank of fuel, will have a volume of about 150 l, and in order to store hydrogen in liquid state a special "thermos" is necessary in which the temperature should be up to 20 K. In the liquid state hydrogen occupies a volume equal to 1/300 of the volume in normal conditions and hydrogen density is 0.0708 kg l⁻¹. The combustion heat amount of 1 l liquid hydrogen is 8496 kJ or 1/4 of the amount of released heat of 1 l gasoline combustion which is equal to 32560 kJ. Besides, liquid hydrogen is about two to three times more expensive than gaseous hydrogen and it is necessary that the containers with liquid hydrogen should have special thermal insulation to prevent hydrogen from evaporating. As ideal thermal insulation does not exist, losses of hydrogen due to evaporation are inevitable. The manufacture of super insulated containers for storing hydrogen in a liquid state at low temperatures presents many problems to the designers and the initial capital investments are great. Another important factor complicating the utilization of liquid hydrogen in automobile transport is the instantaneous evaporation of hydrogen at initial filling of the tank. When, at the beginning, the tank is filled with hydrogen, a larger volume of gas instantly evaporates during the process of cooling the internal surface of the tank. When, at the beginning, the tank is filled with hydrogen, a larger volume of gas instantly evaporates during the process of cooling the internal surface of the tank due to the low temperature of the liquid hydrogen. After filling the tank, in spite of the super insulation, a heat exchange takes place with the environment and hydrogen keeps evaporating resulting in great losses.

To decrease the weight of the tank containing liquid

hydrogen, the DFVLR firm has manufactured a cryogenic container, Dewar type, of aluminum. Its volume is 151 l and one fill of hydrogen is equal to 39 l of gasoline. The tank mass is 43 kg, and with hydrogen, 54 kg at 0.45 MPa. During the first fill of the tank for 30 min, 20 l of liquid hydrogen enter at a temperature of 20 K, and after sufficient cooling of the tank, for about 5 min it is completely filled. With time, because of heat penetrating from the surroundings, the pressure in the tank grows to about 0.01 MPa per hour, therefore a safety valve is provided. This valve releases daily 9 l of liquid hydrogen which, after catalytic treatment directly in the automobile, is turned into water. For safety reasons, the place where the tank is kept is separated by special insulation and provided with a special signal system reacting to hydrogen appearance.

Hydrogen can serve both as an independent fuel or as an additive to petroleum fuel. Using hydrogen as an independent fuel is difficult because of the great mass and volume of the system of its storing (for a run of 350 to 400 km). Another problem is the necessity of taking additional constructive solutions for a normal working process when the engine works with hydrogen; that is why in the near future hydrogen can be used as additional fuel, i.e. as an additive to the basic liquid fuel.

3. METAL HYDRIDES AS ACCUMULATORS OF HYDROGEN

In the late 1960s it was suggested that the so-called metal compounds for storing automobile hydrogen should be used. A hydride is the compound of any element with hydrogen. These compounds react with great volumes of gaseous hydrogen and hold it by a weak bond. Metal hydrides exist in granules or powder form. In upsetting the equilibrium temperature and pressure, the hydrides dissociate and release gaseous hydrogen. At the temperatures of the exhaust gases or the cooling device, the metal hydrides containing hydrogen release it in a gaseous state.

Some hydrides contain more hydrogen per unit volume compared to liquid hydrogen. The hydrogen absorption by metals to form metal hydrides is an exothermal reaction which is reversible and hydrogen can be restored by increasing the temperature or lowering the pressure necessary for the process of absorption. At a given temperature the hydride is in equilibrium with a definite pressure of hydrogen.

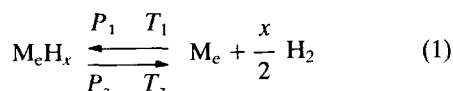
The high safety factor, compactness, the filling with comparatively cheap gaseous hydrogen at low pressure (0.2 to 0.2 MPa) and practically the unlimited term of

work of the alloy assist the hydride systems to store hydrogen for experimental automobiles.

The secondary energy carriers of hydrogen are a prospective form of using hydrogen as a fuel for internal combustion engines. They solve the safety problem in the operation of automobiles with hydrogen fuel and provide the necessary energy reserve without high pressure and very low temperatures.

To utilize hydrides in the energy devices it is necessary to define the rate of the processes hydrogenation and dehydrogenation, to find the optimum conditions for these processes as well as the losses of energy when they are carried out.

The mass content of hydrogen in the hydrides used is within 1 to 10% according to the type of hydride. This provides a high density of hydrogen in the hydride and hence a small storing system (150 to 400 l for 14 kg of hydrogen), in which case the mass of the system is 250 to 1300 kg. Hydrogen accumulators with reversible action should have special absorption-desorption characteristics in which the reaction



is reversible and reacts fast enough for technologically admissible pressures and temperatures [8].

The release of hydrogen is carried out by heating the hydride with liquid from the cooling device and directly by the exhaust gases and the rate of release grows with the rise of temperature.

To charge the hydride accumulator hydrogen is fed under low pressure and at the same time the heat is withdrawn. The process of charging can be carried out many times without deteriorating the energy-consumption of the accumulator. At a given temperature, every hydride is in equilibrium with a definite pressure of hydrogen. Hydrogen consumption and lowering of the pressure in the system decomposition will take place up to the moment when the released hydrogen restores that pressure again. This process depends not only on temperature but on the amount of hydrogen in the solid phase.

This amount is not constant but changes over a wide range. The dependence of the content of the solid phase on the pressure is shown in Fig. 6 for a typical simplified system of metal-hydrogen.

On contact of the gaseous hydrogen with the metal surface the hydrogen molecules absorb along it. Some of these molecules dissociate to atoms which enter the crystal lattice of the metal and occupy specific locations between the metal atoms. As a result, the hydrogen-

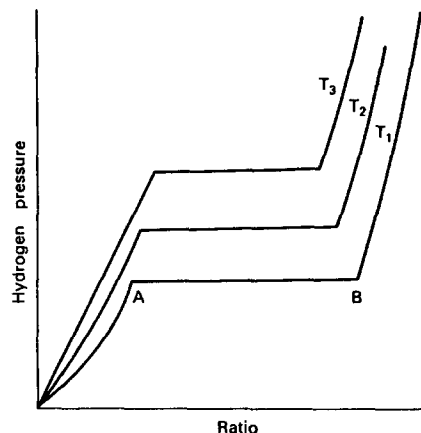


Fig. 6. Isotherm "pressure content" for a typical system metal-hydrogen (the content has been defined as a ratio of the hydrogen to the metal (H/M).

metal ratio (H/M) grows. At higher concentration and pressure of hydrogen a new phase forms. If the pressure continues to increase, absorption of new quantities of hydrogen follows. The curves T₂ and T₃ show the increased temperatures on the pressure-content ratio.

In storing hydrogen in a hydride system one should choose a hydride providing a minimum mass of the system at satisfactory operating characteristics. The hydrides should have high absorption capacity, high density, low amount of heat needed for desorption, explosion safety and fire safety, low cost, as well as a suitable characteristic of pressure change in the temperature range of 293 to 473 K.

Table 3 gives the most important characteristics of some hydrides which can be used as automobile accumulators of hydrogen [9]. A basic problem is the choice of a hydride fully satisfying the above mentioned requirements. In estimating the possibility of utilizing one or another type of a hydride as an automobile accumulator of hydrogen, a major concern is the release of the necessary amount of hydrogen from the hydride at any working condition of the engine at the expense of the heat of the exhaust gases or of the cooling liquid. In connection with this, methods have been offered for the choice of a hydride, making use of a test run cycle which involves the most characteristic working conditions of the engine in town [9]. The methods offered are for an engine burning a gasoline-hydrogen mixture but it can be used when the automobile burns only hydrogen. The hydrides given in Table 3 can be divided into two groups: low temperature hydrides with hydrogen desorption temperatures up to 373 K at a pressure P = 1.0 MPa and high temperature ones.

On a constant heat flux surface of a hydride tank, an

Table 3. Hydride characteristics

Characteristics	Ti ₂ Ni-H _{2.5}	FeTi-H ₂	VH-VH ₂	LaNi ₅ -H _{6.7}	Mg ₂ Cu-H ₃	Mg ₂ Ni-H ₄	Mg-H
Absorption ability of hydrogen in % of the alloy mass	1.61	1.87	1.92	1.55	2.67	3.71	8.25
Heat at desorption, q_s , kJ kg ⁻¹ , H ₂	15.8	14.92	19.12	15.59	32.7	30.6	38.8
Equilibrium pressure at 293 K (when charging) in MPa	0.55	0.29	0.21	0.12	not formed		
Charging	easily			very hard		hard	very hard
Temperature desorption in K							
at $p = 1.0$ MPa	307	325	326	346	591	623	635
at $p = 0.15$ MPa	270	280	288	294	522	540	569
Occurrence of the metal	often	very often	very seldom	seldom		often	
Safety	safe				highly inflammable	safe	highly inflammable
Hydride mass equivalent to the energy of 1 liter gasoline	16.75	14.45	14	17.4	14.65	7.28	3.2
Alloy mass necessary to accumulate 2.5 kg H ₂	155	134	130	161	—	67.5	324
Mass of the combustion device for 2.5 kg H ₂ (the mass of concentration with 0.4 of the mass of the hydride)	217	188	182	225	—	95	50

increase of the temperature of the exhaust gases at the tank input results in their temperature increase at the output too, which brings about a decrease of the heat available for a cycle. Such a dependence is shown in Fig. 7. In the same figure one can see the amount of heat needed for hydrogen desorption per run cycle of some hydrides in the range of equilibrium temperatures at pressures from 0.15 to 1 MPa. For the low-temperature hydrides (LaNi₅-H_{6.7} and FeTi-H₂) the available heat of the exhaust gases exceeds the necessary amount by 2 or 3 times. To avoid overheating the hydride tank and to

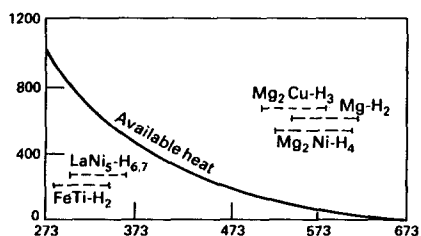


Fig. 7. Dependence of the total amount of available heat (Qa) per cycle of the temperature of the output gases of the hydride tank. The line shows the necessary amount of heat to release hydrogen from the indicated hydrides.

increase the pressure of the hydrogen above the estimated, it is necessary to release the surplus amount of heat which can be done by quantitative regulation of the exhaust gases passing through the hydride tank.

For the high-temperature hydrides (Mg₂Ni-H₄, Mg-H₂, Mg₂Cu-H₃) the available heat from the exhaust gases is not sufficient to release the necessary amount of hydrogen because their utilization as independent accumulators of hydrogen for automobiles is inexpedient.

From the low-temperature hydrides shown in Fig. 7 the ferrotitanium is the most promising because it has good absorption ability and low cost. It satisfies fully the requirements for the equilibrium of the heat necessary for all driving conditions of the automobile [9].

If we add manganese to the ferrotitanium, the crystal lattice expands because of the manganese atoms in it. This leads to stabilization in the hydride phases and lowering of the pressure. The maximum capacity of storing hydrogen of Fe_{0.8}TiMn_{0.2} is about 1.9% and is achieved even at a pressure of 2 MPa and a temperature of 273 to 293 K. This allows the construction of a tank for lower pressure, hence with less weight.

In Table 4 [10] information is given about the actual capacities in storing hydrogen keeping in mind the mass of the tank (the material of which the tank is made is

Table 4. Energy capacity of hydrides as functions of the working pressure (298 K)

Active material	Storing capacity of the active materials, kJ kg^{-1}	Working pressure MPa	Actual storing capacity, kJ kg^{-1}
FeTi	2205	5	1715
FeTi	1960	2	1593
FeTi	1715	1.5	1470
FeTi	1470	1	1347
$\text{Fe}_{0.8}\text{Ti Mn}_{0.2}$	2327	5	1715
$\text{Fe}_{0.8}\text{Ti Mn}_{0.2}$	2266	2	1873
$\text{Fe}_{0.8}\text{Ti Mn}_{0.2}$	2205	1	1960

Table 5. Characteristics of the combined hydrides

Coefficients	FeTi, 100%	FeTi, 70% Mg_2Ni_2 , 30%	FeTi, 60% MgNi , 40%	FeTi, 50% Mg_2Ni , 50%	FeTi, 70% Mg , 30%	FeTi, 60% Mg , 40%	FeTi, 50% Mg , 50%
Mass, kg	188	160	150	140	146	132	118
Mass decrease compared to FeTi, %	0	15	20	25.5	22.5	30	37

steel and is 25 to 30% of the total mass at a pressure of 5 MPa, 15 to 20% at a pressure of 2 MPa and 10% at a pressure of 1 MPa).

By combining familiar low-temperature hydrides, it is possible depending on the working conditions, to obtain a hydride suitable to store hydrogen at temperatures of 353 to 373 K.

In the research of high-temperature hydrides, the optimal system proves to be $\text{Mg-Mg}_2\text{Ni}$. The theoretical maximum capacity of storing hydrogen (calculated as a weight ratio) as a function of the Ni content in the system is shown in Fig. 8. The continuous curve shows the capacity related to the mass of the metal and the dotted curve shows the content of hydrogen related to the hydride mass. To achieve the highest possible capacity it is necessary to maintain a very low nickel content. Practically, the addition of nickel provides fast kinetics because of the formation of Mg_2Ni phase. The optimum content of nickel in the alloy is about 5%. Maximum capacity of storing hydrogen at this content of the alloy is 7% by weight.

The independent utilization of high-temperature hydrides as automobile accumulators of hydrogen is difficult but they can be used in combination with low-temperature hydrides which considerably diminishes the

mass of the hydride system. The characteristics of the combined systems are given in Table 5 [9 and 11].

The hydride systems have a certain heat inertness. An insufficient encompassing of the transient working conditions of the engine should be expected when hydrogen consumption sharply increases. The transient conditions usually follow an idle condition where the surplus heat

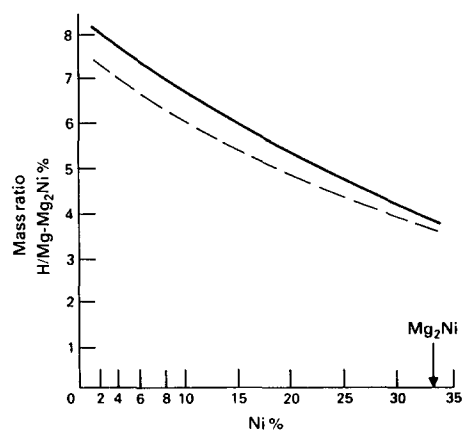


Fig. 8. Theoretical capacity (defined as weight ratio) for storing hydrogen of the hydride $\text{Mg-Mg}_2\text{Ni-Ni-H}_4$ as a function of the content of nickel.

amount is practically missing and it is expedient to utilize the surplus amount of heat from other areas of the cycle to store hydrogen and consequently using it in the transient conditions. This is achieved by putting a collecting container for hydrogen after the hydride tank. It can also serve to collect the released hydrogen due to the metal hydride inertness when the engine stops.

When the hydrogen pressure in the collecting container changes from 1.0 to 0.15 MPa to cover the necessary consumption of hydrogen for the transient conditions, the volume of the container should be about 3 l. The utilization of a collecting container is indispensable from the point of starting the engine.

The constructive design of the metal-hydride tank is shown in Fig. 9. It consists of a set of pipes full of metal which at one end are joined together in a common collector designed to collect hydrogen and at the other end they are closed. The pipes are arranged in a casing of rectangular cross-section acting as a shield and as a main for the exhaust gases when heating the hydrides. The metal in the pipes is 50 kg and the total mass of the tank is 67 kg. When closed the tank contains 0.75 kg of hydrogen.

To improve the exhaust gases heat emission and for better distribution of water when loading, reflectors can be installed in the tank. Figure 10 [9] shows such a construction. The hydride tank is a metal container with a rectangular shape in which the nine hydride elements are arranged in three lines, three in each line, joined in a common collector providing additional space for collecting hydrogen. The elements are manufactured in the form of pipes with a diameter of 50 mm, 900 mm long and walls 1 mm thick. Filters are installed along the

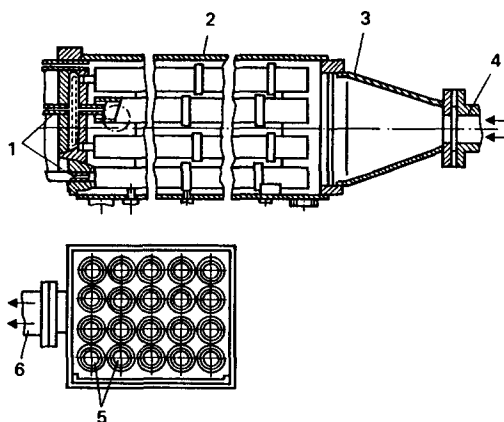


Fig. 9. Hydride tank: 1 = hydrogen pipeline; 2 = casing; 3 = diffuser; 4 = pipeline to lead the exhaust gases from the engine; 5 = hydride elements; 6 = pipeline to lead the exhaust gases from the tank.

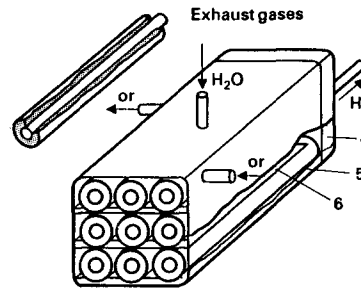


Fig. 10. Hydride tank: 1 = filter; 2 = hydride; 3 = hydride element shield; 4 = common collector; 5 = hydride tank shield; 6 = directing elements; 7 = hydride elements belying cleats.

longitudinal axis of the elements providing a path for the hydrogen leading from the zones of the reaction along the whole length and preventing the formation of an inefficient layer of hydride in the center of the elements. Reflectors are installed along the internal walls of the metal container. The tank shield is made of duraluminum sheet and is isolated with asbestos fabric.

Figure 11 shows the characteristics of a hydride tank utilizing FeTi, fitted in a bus with a mass of 7250 kg and running at a speed of 95 km h⁻¹ [12].

The total holding capacity of the system is calculated for 14.5 kg of hydrogen. The total useful holding capacity of the tank has been estimated at 12.5 kg of hydrogen, the hydrogen constituting 1.25% by mass. The tank mass is 508 kg.

Table 6 gives the volume-mass characteristics of various systems of storing hydrogen for automobiles, providing 418 km run [13].

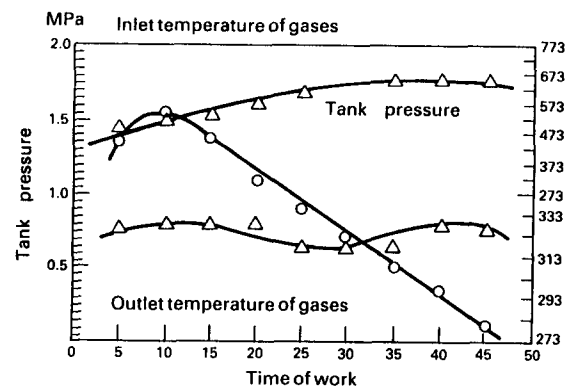


Fig. 11. Characteristics of the hydride tank.

Table 6. Characteristics of systems for storing hydrogen

	Gasoline	Liquid hydrogen	Compressed hydrogen	Metal hydride MgH ₂
<i>Fuel</i>				
Mass, kg	53.3	13.4	13.4	181
Volume, m ³	0.07	0.19	1.0	0.23
<i>Tank</i>				
Mass, kg	13.6	181	1361	45.4
Volume, m ³	0.08	0.28	1.53	227
Total mass (with the fuel), kg	67	195	1374	227

4. HYDROGEN SUPPLY TO THE ENGINE

The chemico-physical properties of hydrogen and the characteristics of its storage and in some cases the possibility of obtaining it on board the automobile define the requirements to the feed and control systems in the transformation of the gasoline engine to burn hydrogen.

The hydrogen supply systems of the engines should satisfy the following important requirements: good sealing of all parts to prevent hydrogen leakage; qualitative control of the fuel-air mixture due to the wide range of combustibility of the hydrogen-air mixture; fuel metering in conformity with the working conditions of the engine.

Hydrogen supply to the engine can be carried out in one of the following ways: feeding into the engine intake manifold (under low pressure); feeding into the conventional or transformed for gaseous fuel carburetor; feeding close to the feed valves of the engine; direct injection into the engine cylinders (under high pressure).

The first two methods provide steady work of the engine only together with actions like: partial recirculation of the exhaust gases, supplementary water to the fuel mixture as well as adding gasoline to the fuel mixture. In partial recirculation of the exhaust gases of the engine, because of mixing of the inert components contained in them, backfire is prevented and soft work of the engine is provided at stoichiometric content of the hydrogen-air mixture.

At the same time due to lowering of the maximum cycle temperatures the emission of NO_x in the exhaust gases decreases. The amount of the recirculating gases does not exceed 10 to 20% of the fuel mixture entering the engine [6 and 13]. A greater amount of recirculating gases brings about additional losses when filling the engine cylinders. Unlike recirculation of exhaust gases

supplementary water or gasoline (injected into the intake manifold) does not bring about deterioration of the engine feeding.

Figure 12 [7] shows a diagram of an air, hydrogen and water mixer, mounted on engines burning hydrogen manufactured by Mercedes Benz.

Figures 13, 14 and 15 show ways of feeding hydrogen directly close to the feed valves.

Feeding hydrogen (Fig. 13) to the combustion chamber is carried out by opening manifold 1 which is done by the filling valve in the intake stroke and, due to the

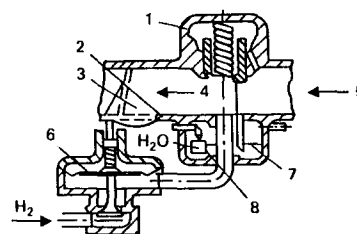


Fig. 12. A diagram of a mixer of water, hydrogen and air for an automobile engine: 1 = modernized carburetor; 2 = throttle valve; 3 = eccentric; 4 = air, hydrogen and water mixture; 5 = air inlet; 6 = chamber; 7 = water; 8 = float.

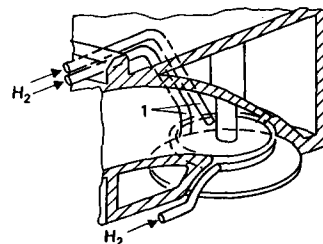


Fig. 13. A diagram of a hydrogen metering device: 1 = inlet pipe.

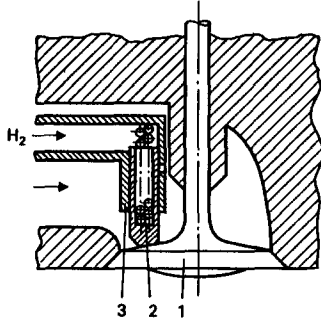


Fig. 14. A diagram of a hydrogen metering device: 1 = valve; 2 = piston; 3 = casing.

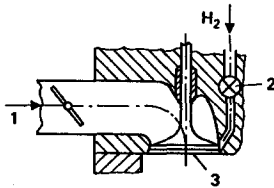


Fig. 15. A diagram of a hydrogen metering device: 1 = air; 2 = channel; 3 = valve.

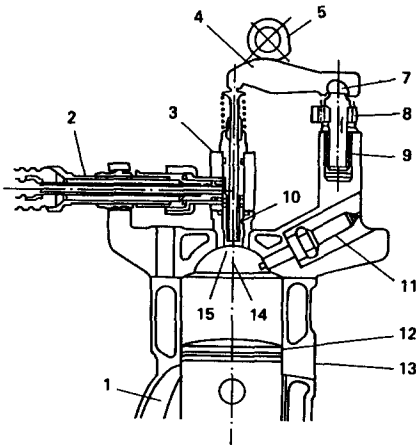


Fig. 16. Diagram of a device for hydrogen injection into the cylinder of a two-stroke engine: 1 = scavenging port; 2 = hydrogen pipeline insulation; 3 = sprayer; 4 = rocker; 5 = camshaft; 6 = toothed rack; 7 = heel; 8 = gear wheel; 9 = screw; 10 = valve; 11 = spark plug; 12 = piston upper part; 13 = outlet; 14 = combustion chamber; 15 = injector.

evacuation in the engine cylinder, hydrogen enters the combustion chamber.

Hydrogen introduction (Fig. 14) is carried out by a metering device providing hydrogen feed directly to the filling valve 1. The central piston 2 is in constant contact with the surface of valve 1 by a spring and due to hydrogen pressure. The device is adjusted so that it is opened after the filling valve 1 is opened and is closed earlier, and the time during which the port is open is half the time of the open position of the filling valve.

The introduction of hydrogen shown in Fig. 15 is similar to that in Fig. 13 but it is carried out in a different way.

The ways of hydrogen feed (Figs 13, 14 and 15) give the possibility of non-throttle control of the engine which brings about lower mechanical losses in the process of filling and evacuation in the engine cylinders and that brings about a reduction of the amount of oil introduced through the piston rings into the combustion chamber burnt together with the fuel.

Hydrogen introduction into the intake manifold, into the carburetor or directly to the filling valves of the engine presents a problem based on the low density of hydrogen. This brings about a loss of volume efficiency because hydrogen displaces part of the air and the specific power of the engine is lowered by about 20% compared to gasoline [14].

Best results are obtained when hydrogen is injected directly into the engine combustion chamber. In this way backfire in the intake manifold is excluded and the maximum power can be increased by 10 to 15% [6].

Figure 16 shows the diagram of a device for direct hydrogen injection into a two-stroke engine [15]. The injector is in the center of the cylinder head. The injector valve is opened by a camshaft which moves with the speed of the crankshaft. To overcome the back pressure of condensation, a small pump is used to increase hydrogen pressure. The place of the rocker reference point can be changed in the process of injection and the run of the valve can be changed according to the rate of injection. This is provided by the small gear wheel, turned by the toothed rack connected with the fuel-feed pedal.

The analysis of the results of the study of engines burning hydrogen and various systems of feed into the intake manifold shows that most expedient from the standpoint of safety is the feed system with electromagnetic valves [Fig. 17], providing hydrogen feed in the period when the filling valves are open [8].

The duration of opening of electromagnetic valve 3 changes from 2 to 30 ms which corresponds to the change of the cycle feed of hydrogen in the interval of speed and

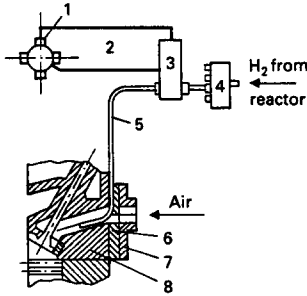


Fig. 17. A diagram of a hydrogen metering system with electromagnetic valves: 1 = control distributor of the electromagnetic valves; 2 = wires; 3 = electromagnetic valves; 4 = manifold; 5 = pipes; 6 = attachment; 7 = intake manifold; 8 = cylinder head.

load working conditions of the engine, provided the hydrogen fuel of the double reduction gear enters under pressure of 0.12 MPa.

When the carburetor engine burns a gasoline and hydrogen mixture, additional difficulties arise in connection with their mixing in the carburetor. Besides, with the constant hydrogen consumption the relation of

hydrogen to hydrogen plus gasoline can not be optimal. This determines the necessity of using alternating flow rate of hydrogen for the corresponding operating conditions of the engine.

Figure 18 shows a system worked out on the basis of a double chamber carburetor [6].

An additional diffusor 8 with throttle valve 9 is mounted to take the hydrogen-air mixture from the double reduction gear to the carburetor. Hydrogen pressure at the inlet of the mixing chamber is 0.1 MPa.

The throttle valve of the primary chamber of the carburetor 5 is kinematically connected with a crank mechanism with throttle valve 9. The single-ended elastic unit 14, in the process of opening valve 5, provides reciprocating advance turning of valve 9 and in the various operating conditions of the engine air, gasoline and hydrogen are fed in at a given ratio.

When driving in town conditions, for a considerable part of the time the engine works at idle condition, and in order to lower the consumption of hydrogen, there is an additional device to the system which turns off hydrogen feed in such conditions. The device consists of an electromagnetic valve 10 and a control system consisting of an electron unit 13 and contacts 1, 2 and 12. Hydrogen feed is interrupted by a special device when the engine is fully loaded, to keep the set power factors.

At forced idle running, contacts 1 are closed and a pulse arises from the distributor-and-contact breaker unit at the input of the electronic unit 13. At rotation rate of the crankshaft of about 1600 min^{-1} the electronic unit does not supply voltage to the output and the electromagnetic valve interrupts the hydrogen feed and at rate below 1200 min^{-1} the output voltage is 12 V and the engine is fed only with hydrogen. At maximum load, when the engine works only with gasoline-air mixture, contacts 2 are disconnected, valve 10 is closed and interrupts the hydrogen feed.

When the hydrogen reserve is consumed the driver closes the air valve 7 and the sensor contact 12 closes the hydrogen main with the help of the electromagnetic valve 10. At the same time is closed contact "b" of the sensor 12 supplying voltage 12 V of the electromagnetic valve 4 turning on the independent system of idle running of the carburetor when working with gasoline-air mixture.

The principle diagram of a system with conversion of a double-chamber carburetor for the engine to work with alternating hydrogen consumption is shown in Fig. 19. The changes consist in the following: the main metering system (for gasoline) of the secondary chamber is isolated; so is the transient system at the secondary chamber. The small diffusor is removed and the injector

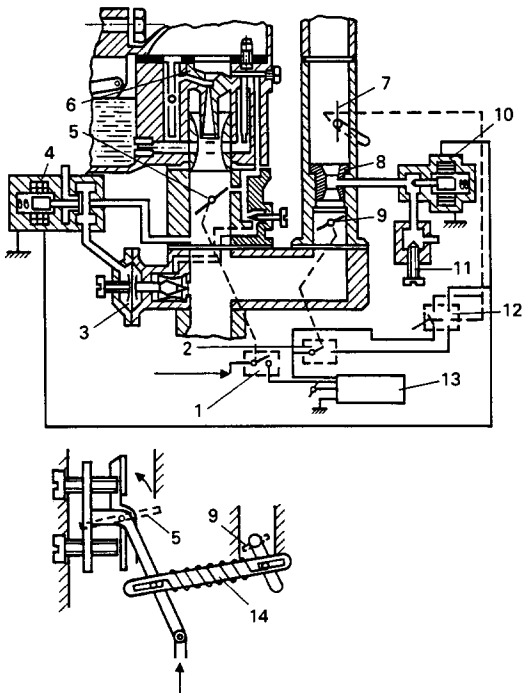


Fig. 18. A diagram of a feed system to feed the engine with gasoline-hydrogen fuel: 1, 2, 12 = contacts; 3 = air chamber; 4 and 10 = electromagnetic valves; 5 and 9 = throttle valves; 6 = carburetor; 7 = air valve; 8 = supplementary diffusor; 11 = adjusting screw; 13 = electronic unit; 14 = elastic unit.

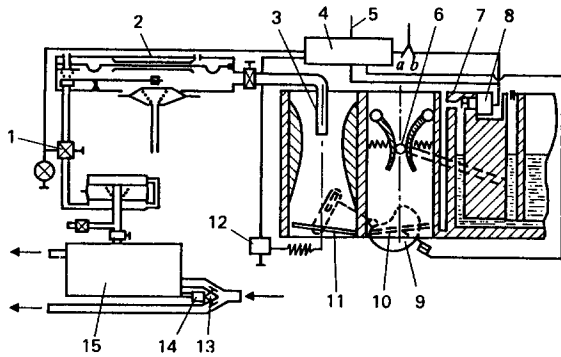


Fig. 19. A diagram of a fuel device of an automobile for the engine to operate with alternating hydrogen consumption.

3 is mounted in the smallest cross section of the large diffuser. The main metering system and the idle running system (burning gasoline) at the primary chamber have been kept with the same characteristics but an electromagnetic valve 8 has been mounted to the fuel jet 7 of the idle running system. The kinematic connection between the spindles of the primary and secondary throttle valves has been changed as shown in the diagram. Hydrogen is kept in a special hydride tank mounted in the automobile trunk. The system provides work of the engine with supplementary hydrogen, it stops gasoline flow to the idle running system when the engine works with supplementary hydrogen and turns off hydrogen feed when the engine works at forced idle running. These conditions are provided by control unit 4.

The operation of the system is as follows. When the engine is switched on by the contact key, voltage 12 V is supplied to the control unit. At the same time the control unit receives a signal through connection 5 to turn the crankshaft which defines the voltage supply to the electromagnetic valve 1 which lets hydrogen to the vacuum regulator 2. From the vacuum regulator, through a metering valve, hydrogen is injected by injector 3 into the secondary mixing chamber of the carburetor. At the same time from the control unit voltage is supplied to the electromagnet 12, which provides turning of the throttle valve 11. At idle running of the engine, throttle valve 10 of the primary mixing chamber is closed and the control unit does not supply voltage to the electromagnetic valve 8 which stops gasoline flow to the fuel jet 7 of the idle running device. When opening throttle valve 10 the electric circuit is interrupted, the electromagnetic valve opens and lets gasoline in so that the combustion process is not disrupted until necessary rarefaction is achieved in the

diffusers to operate injector 7 of the main metering system for work with gasoline. With the opening of throttle valve 10 the secondary throttle valve 11 is also turned but according to a definite law let by the profile cam 9. The law of turning valve 11 in a function of turning valve 10 has been deduced from the condition of realization of given ratios of hydrogen and gasoline in the working mixture at characteristic working conditions of the engine aiming at minimum content of CO, CH and NO_x in the exhaust gases and gasoline economy of 30 to 40%. The quantitative hydrogen regulation is carried out in the vacuum regulator 2 according to the rarefaction in the secondary mixing chamber. When the engine works at forced idle running and crankshaft rotation rate of 400–500 min⁻¹ greater than the minimum stability rate at idle running the control unit 4 interrupts the voltage to the electromagnetic valve 1 and hydrogen feed is stopped.

If the engine burns a gasoline–hydrogen mixture and stops because of a breakdown, the crankshaft rotation rate becomes zero, the control unit interrupts the voltage to the electromagnetic valve 1 and hydrogen feed to the vacuum regulator is stopped. When the engine burns only gasoline the switch is in position c and the control unit does not operate and hydrogen is not fed to the vacuum regulator.

Hydrogen pressure at the hydride tank output 15 depends on the amount of heat transferred by the exhaust gases to the metal hydride and is kept below the admissible limit by the sensor 14 and the exhaust gases distributor 13.

With engines working with hydrogen it is possible to use a device applied in gas motors [8]. With such a feed system it is impossible to make full use of the advantages of hydrogen as a fuel. The application of such a device is rational with engines burning gasoline and supplementary hydrogen. Feeding hydrogen in the compression stroke is most promising but that requires fundamental structural changes of the engine.

5. CONSTRUCTIVE SOLUTIONS OF AUTOMOBILES WHEN THE ENGINE BURNS WITH HYDROGEN OR WITH SUPPLEMENTARY HYDROGEN TO THE CONVENTIONAL FUELS

Hydrogen application as a main fuel or as supplementary fuel to the conventional fuels has imposed the choice of various constructive solutions.

Figure 20 shows a diagram of the fuel device for an automobile with liquid hydrogen [16]. The liquid hydrogen tank has a spherical shape and is thermally

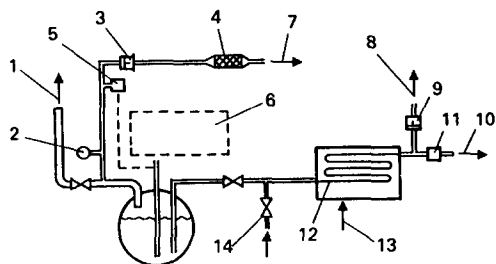


Fig. 20. A diagram of a fuel device for an automobile burning liquid hydrogen: 1 = a pipe to release gaseous hydrogen when loading; 2 = pressure gauge; 3 = release valve; 4 = catalyst to oxidize the naturally evaporated hydrogen; 5 = valve; 6 = heater 12 V; 7 = oxidized hydrogen outlet; 8 = outlet; 9 = outlet valve (0.3 MPa); 10 = hydrogen feed to the engine; 11 = switch; 12 = heat exchanger; 13 = quenching bath; 14 = feed pipeline.

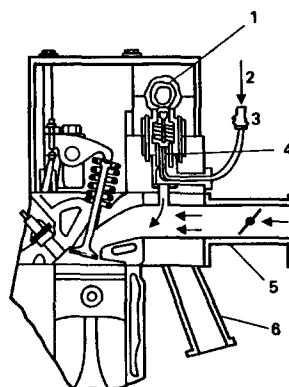


Fig. 22. A diagram of a valve mechanism to feed hydrogen: 1 = cam; 2 = hydrogen; 3 = hydrogen pipeline insulation; 4 = valve; 5 = intake manifold; 6 = exhaust manifold.

insulated on the outside. In the tank is mounted a small electric heater which heats the hydrogen to increase the pressure in the upper part of the tank. With the help of the heat exchanger and the quenching bath, hydrogen is heated and cooled to normal temperature and fed to the engine.

The device described is supplied with a catalyst through which the naturally evaporated hydrogen passes to be oxidized.

Figure 21 shows the disposition of the main elements of the fuel device for liquid hydrogen of an automobile [16]. The mass of the the tank is 120 kg, displacement 230 l and the tank is in the trunk. The internal part of the tank is made of stainless steel, and the external is made of aluminum. The distance between the two walls is 100 mm and is filled with insulating and screening materials to keep the temperature of the tank low. Hydrogen is fed

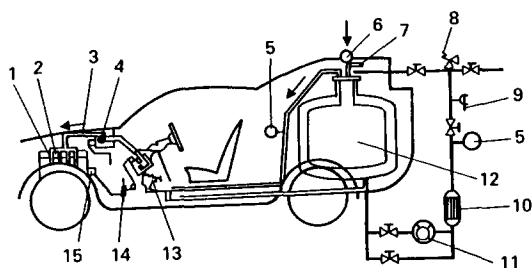


Fig. 21. A diagram of the disposition of the main elements of a fuel device for liquid hydrogen of an automobile: 1 = filling valve; 2 = engine; 3 = pipeline; 4 = regulator; 5 = pressure gauge; 6 = level gauge; 7 = feed pipeline with a valve; 8 = safety valve; 9 = safety membrane; 10 = heat exchanger; 11 = pump; 12 = liquid hydrogen tank; 13 = shut-off cock; 14, 15 = vacuum mechanism.

only when the filling valve is open. This method of feeding is carried out by a valve mechanism shown in Fig. 22. The valve letting hydrogen in is opened simultaneously with the filling valve of the engine and is closed after 90° turning of the crankshaft. The hydrogen pressure is 0.4 to 0.5 MPa. The change in the hydrogen consumption is carried out by a double reduction gear with two needle valves.

The clear opening of the first valve is maintained by a mechanism with a vacuum drive depending on the engine rotation frequency and of the second one through a ganging by the gas pedal. Hydrogen pressure (0.4 to 0.5 MPa) is provided by the pump 11.

Air is supposed to be let out to prevent leaning of the fuel mixture. The hydrogen pipeline is insulated and maintains a temperature of about 143 K at the point of injection which allows considerable improvement of the filling of the engine cylinders.

The engine characteristics are improved with the cooling of hydrogen (Fig. 23). With hydrogen feed at a temperature of 143 K the output power almost coincides with that of gasoline and at a normal temperature of hydrogen the power is lower.

The principle diagram of a system to test a two-stroke engine in laboratory conditions when burning liquid hydrogen is shown in Fig. 24 [15]. Hydrogen is injected into the engine under pressure of 1.0 MPa (the way of injecting is shown in Fig. 16). A flowmeter with calibrated openings, a manometer in front of the flowmeter and a thermocouple are used to measure the hydrogen consumption more precisely. The amount of fuel injected into the engine is controlled by control devices, while fine control is carried out by valve 8. Liquid nitrogen is used to cool the hydrogen which is to be

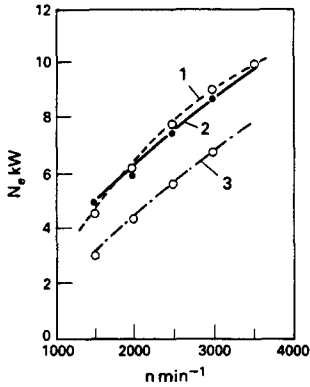


Fig. 23. Effect of the cooling of hydrogen on the engine power: 1 = power of the engine burning gasoline; 2 = power of the engine burning cooled hydrogen (143 K); 3 = power of the engine burning hydrogen at normal temperature.

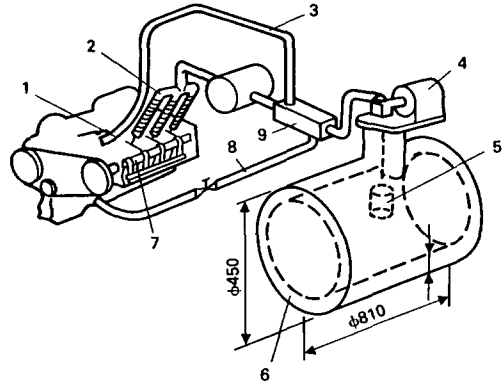


Fig. 25. A diagram of a combustion device of an automobile burning liquid hydrogen: 1 = sprayer; 2 = isolated hydrogen pipeline; 3 and 8 = pipelines; 4 = electromotor; 5 = pump; 6 = liquid hydrogen tank; 7 = camshaft; 9 = heat exchanger.

injected. The temperature of the walls of the engine cylinders, of the cylinder head and the temperature around are measured with the help of temperature measuring recorders.

Power is measured with an electric dynamometer for eddy current. It has been established that the advanced ignition can be controlled with the temperature of the hydrogen, but for the detonation the temperature of the combustion chamber walls is of greater consequence.

Figure 25 shows a diagram of a combustion device of an automobile burning liquid hydrogen [15]. The liquid hydrogen tank is a cylinder with double walls, the internal wall being made of stainless steel 1 mm thick and the external one also of stainless steel but 2 mm thick. The distance between the two walls is 50 mm, the

walls are insulated with aluminum foil and the space between them is a vacuum. Evaporation losses are 8–9% per day. The most interesting element is the pump because of the following reasons: a suitable lubricant cannot be provided for very low temperatures; liquid hydrogen viscosity is very low, 1/70 of that of water; the material for the friction surfaces should have a low thermal expansion coefficient; the suction of the liquid phase of hydrogen is hampered; there should be no lapses in the pump.

In Fig. 26 we have shown the diagram of the pump. Its parameters are: 15 mm diameter and 7 mm stroke. The cylinder must be made of a metal and the external layer of the piston 2 of such a material which has minimum friction drag. In order to maintain constant radial

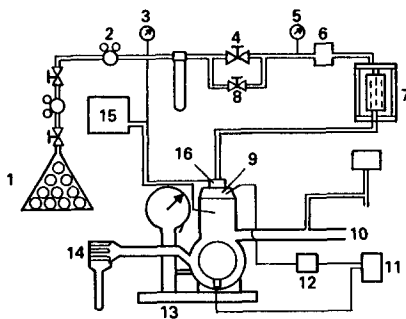


Fig. 24. A diagram of a laboratory system to test a two-stroke engine burning liquid hydrogen: 1 = a tank for hydrogen under high pressure; 2 = pressure regulator; 3 and 5 = manometers; 4 = brake valve; 6 = compensation reservoir; 7 = liquid nitrogen tank; 8 = control valve; 9 = piezomanometer; 10 = outlet manifold; 11 = oscilloscope; 12 = piezointensifier; 13 = dynamometer; 14 = air flowmeter; 15 = temperature recorder; 16 = hydrogen feeder.

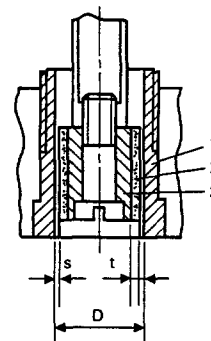


Fig. 26. Piston and cylinder of a pump for liquid hydrogen: 1 = cylinder; 2 = external piston surface, made of a material with minimum drag; 3 = piston; S = clearance; D = cylinder diameter; t = size of material with minimum drag.

clearance of 2–3 mm between the piston and the cylinder the following connection is required:

$$t = \frac{D}{2} \left(\frac{\alpha_1 - \alpha_2}{\alpha_2 - \alpha_3} \right) \quad (2)$$

where α_1 , α_2 and α_3 are the coefficients of thermal expansion of the materials 1, 2 and 3.

An experimental automobile UCLA (USA) designed for city traffic [11] has worked with compressed hydrogen. In the engine the degree of condensation has been lowered from 11.7 to 8.9, the phases of gas distribution have been altered and a device to limit the temperature of the fuel mixture has been mounted. Recirculation of 25% of the exhaust gases is carried out to lower the rate of pressure increase to prevent backfire and to lower the nitric oxides. To ignite the fuel mixture, spark plugs Champion BL-7V have been used with distance between the electrodes 0.9 mm and ignition advance angle 17 to 20° at 6500 min⁻¹. Hydrogen is kept in two bottles of 136 kg each under the front seats, each of them containing 1.36 kg of hydrogen under pressure of 41 MPa. Pressure lowering is provided by a double reduction gear. When there is no thinning in the intake manifold, the electromagnetic valve, controlled by a pressure pick-up, interrupts the hydrogen feed.

For the time being hydrogen storing in metal hydrides is of the greatest practical interest for internal combustion engines.

Figure 27 shows a fuel device of VAZ 2101 with hydride storing of hydrogen [9]. The hydride system of storing hydrogen is on the basis of ferrotitanium. The system is characterized with the coordinated work of the hydride tank and the engine. The heat of the exhaust

gases taken to decompose the hydride and hydrogen release are regulated, according to the consumption, by a system consisting of a pressure relay 7 and an electromagnetic switch 16 in the blast pipe. The control system provides practically constant pressure of the hydrogen in the hydride tank no matter what the engine working conditions are. When lowering the average pressure in the tank the relay starts a mechanism to open and close the valve and a greater amount of exhaust gases pass through the hydride tank to restore the hydrogen pressure. When the pressure is increased, the valve closes and can stop the exhaust gases completely. The safety valve 6 starts operating if the operating pressure is considerably increased.

Hydrogen enters the combustion chamber of the engine through the high pressure reducer 11 and the all-conditions vacuum consumption regulator 12. To the basic elements of the combustion chamber have been included the carburetor-mixer, providing gasoline-hydrogen mixture, only hydrogen or only gasoline, and the electromagnetic valve 9 with electronic control 10, switching off hydrogen feed at forced idle run and when the engine stops.

Loading the hydride tank with hydrogen is done through the cock 5. The heat released from the hydride in the process of loading is taken away with water fed through pipe 4 and flowing out through blast pipe 2. To prevent water entering the exhaust system of the engine, the intake pipe 17 is at a higher level than the water when loading. The disposition of the basic elements of the system is shown in Fig. 28. The tank for storing hydride is in the front part of the trunk and with the help of a metal pipe it is connected with the distributor of the exhaust gases, which is before the second stage of the silencer. Some additional devices are mounted to control the tank work. The automobile tests show that the exhaust gases do not contain CO, and CH and NO_x.

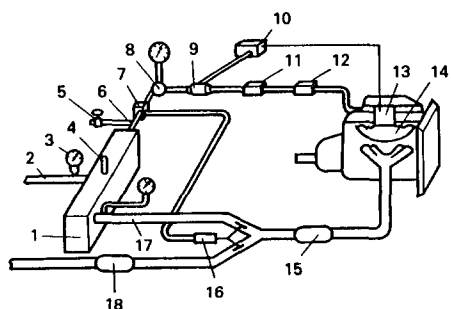


Fig. 27. Diagram of a fuel device of an automobile with hydride storing of hydrogen: 1 = hydride tank; 2 = blast pipe; 3 = thermometer; 4 = water pipe; 5 = hydrogen feeding cock; 6 = safety valve; 7 = relay; 8 = pickup; 9 = electromagnetic valve; 10 = electronic control block; 11 = reducer; 12 = all-conditions regulator; 13 = carburetor; 14 = engine; 15 = first stage of silencer; 16 = electromagnet with a valve; 17 = intake manifold; 18 = second stage of silencer.

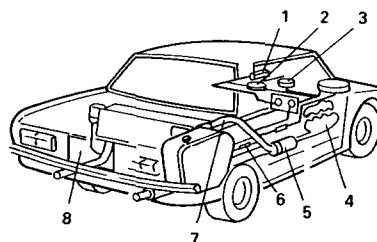


Fig. 28. A diagram of the disposition of the basic elements of a fuel device with hydride stored hydrogen in automobile VAZ-2101: 1 = electronic control block; 2 = reducer; 3 = all-conditions regulator; 4 = carburetor-mixer; 5 = first stage of silencer; 6 = electromagnet with valve; 7 = exhaust manifold; 8 = hydride tank.

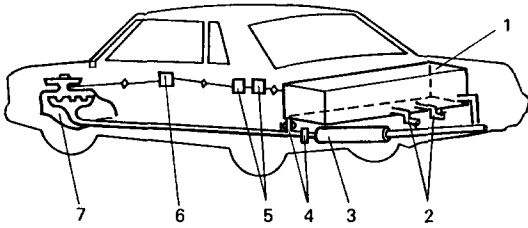


Fig. 29. Diagram of the disposition of the basic elements of a hydride fuel device of an automobile: 1 = hydride tank; 2 = water-flow tube; 3 = silencer; 4 = control valves; 5 = control system; 6 = regulator; 7 = engine.

are below the admissible standard. Supplementary hydrogen lowers gasoline consumption to 40% and raises the engine heat economy by 10–15%.

Another diagram of the disposition of the basic elements of the fuel device with hydride storing of hydrogen in the automobile is shown in Fig. 29 [17]. The hydride tank (shown in Fig. 30) is mounted in the automobile trunk. It consists of 9 cylinders diameter 76 mm and length 700 mm, calculated for 200 kg of metal hydride. When loading, the tank is cooled down to a temperature of 278 K by a water-flow tube between the cylinders, which is also used for the exhaust gases in the process of heating. The changes in the engine are: an increase of the degree of compression, replacing the fuel feed system and regulation of the ignition advance angle from 5 to 10° before top dead center. Hydrogen is fed through a low pressure reducer into a mixer from which, together with the air, it enters a simplified carburetor. The engine power is regulated by throttling the flow of the hydrogen–air mixture.

The combined hydride–liquid system of feeding with hydrogen in the automobile Chevrolet is shown in Fig. 31 [18 and 19]. The engine is started with liquid hydrogen. The hydride tank is heated by cooling liquid of the engine and is set in action after the heat conditions are stabilized. The gas phase of the liquid hydrogen is

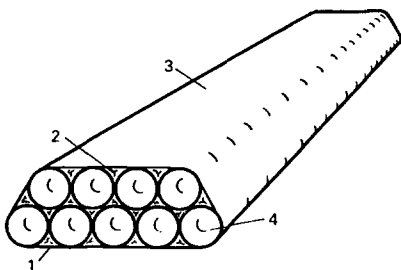


Fig. 30. Diagram of a hydride tank: 1 = hydride elements; 2 = space for the passage of water or exhaust gases; 3 = tank casing; 4 = metal hydride.

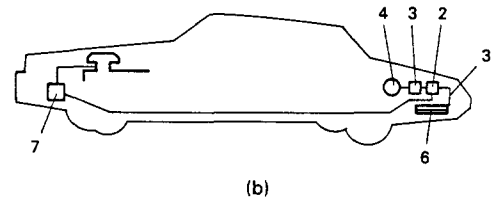
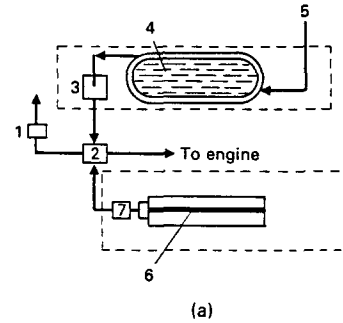


Fig. 31. Diagram of hydride-liquid fuel device for hydrogen of an automobile: 1 = oxidizer; 2 = receiver; 3 = electromagnetic valve; 4 = liquid hydrogen tank; 5 = intake manifold; 6 = hydride tank; 7 = regulator.

used to top the hydride tank, by which lowering of losses, due to hydrogen evaporation is achieved. A mass of 6.4 kg of hydrogen is stored in the hydride tank. When heated up to 343 K, hydrogen is released under pressure of 1–2 MPa. The liquid hydrogen tank has a mass of 41 kg and contains 3.8 kg of hydrogen. The basic parts of the system are mounted in the trunk.

6. DEFINING THE CHARACTERISTICS OF INTERNAL COMBUSTION ENGINES AND THEIR ALTERATION WHEN BURNING SUPPLEMENTARY HYDROGEN.

When organizing the work of internal combustion engine automobiles with supplementary hydrogen to the gasoline–air mixture, the following ways of dosing hydrogen are used [6]:

- (1) constant feed of the same quantity of hydrogen, irrespective of the engine working conditions;
- (2) controlled hydrogen feed, i.e. maintaining a certain constant ratio $H_2/H_2 + \text{gasoline}$ in the fuel mixture (for example 10% of the gasoline quantity for all working conditions of the engine).

When the internal combustion engine is burning supplementary hydrogen at idle, it usually burns only hydrogen and air. At fractional load the engine burns liquid fuel, air and hydrogen simultaneously fed into the

cylinders [20]. At maximum loads the internal combustion engines burn only liquid fuel.

When defining the characteristics of the four stroke carburetor engines burning supplementary hydrogen to the gasoline–air mixture, one must keep in mind the two types of fuel in the fuel mixture. The physico-chemical properties of gasoline and hydrogen are different and that imposes the correction in the dependences for the defining of the engine characteristics [17].

The percentage content of hydrogen in the gasoline–hydrogen mixture is defined by the expression:

$$H_2 = \frac{G_{H_2}}{G_g + G_{H_2}} 100\% \quad (3)$$

where G_g and G_{H_2} are the consumption of gasoline and hydrogen per hour, kg h^{-1} .

The consumption of gaseous hydrogen per hour is defined by the expression

$$G_{H_2} = Q_{H_2} \times \rho_{H_2}, \text{ kg h}^{-1} \quad (4)$$

where ρ_{H_2} is hydrogen density at the time of testing, kg m^{-3} and Q_{H_2} is the volumetric consumption per hour of hydrogen, $\text{m}^3 \text{h}^{-1}$.

The volumetric consumption rate of hydrogen Q is defined with the help of a rotometer used to measure the air consumption, tared for hydrogen. The volumetric consumption rate is calculated with the formula

$$Q_{H_2} = K Q_{H_2}' \left(\frac{\rho_{H_2}'}{\rho_{H_2}} \right)^{1/2}, \text{ m}^3 \text{h}^{-1} \quad (5)$$

where K is a correction coefficient, giving the taring of the rotometer with hydrogen; G_{H_2} is the hydrogen consumption, measured with the rotometer, $\text{m}^3 \text{h}^{-1}$; ρ_{H_2}' is the density of hydrogen at taring with the rotometer, kg m^{-3} and ρ_{H_2} is the actual density of hydrogen, kg m^{-3} .

When the engine burns hydrogen supplementary to the gasoline–air mixture, the air ratio is defined by a direct measuring of the quantity of hydrogen, fed to the engine for a definite time, e.g. per hour:

$$\lambda = \frac{G_{\text{air}}}{G_g l_{\text{th}_g} + G_{H_2} l_{\text{th}_{H_2}}} \quad (6)$$

where G_{air} is the consumption rate of air, kg h^{-1} ; G_g is the consumption rate of gasoline, kg h^{-1} ; G_{H_2} is the consumption rate of hydrogen, kg h^{-1} ; l_{th_g} is the theoretically necessary amount of air for the combustion of 1 kg of gasoline, kg kg^{-1} ($l_{\text{th}_g} \approx 14.88 \text{ kg kg}^{-1}$) and $l_{\text{th}_{H_2}}$ is the theoretically necessary amount of air for the combustion of

1 kg of hydrogen, kg kg^{-1} , ($l_{\text{th}_{H_2}} \approx 34.5 \text{ kg kg}^{-1}$).

The rated efficiency is the ratio of the quantity of heat

converted into rated work in the engine cylinders to the total quantity of heat consumed Q_t to obtain this work:

$$\eta_i = \frac{Q_i}{Q_t} = \frac{P_i V_s}{G_{cg} H_{lg}} \quad (7)$$

where $Q_i = p_i V_s \times 10^3$, kJ cycle^{-1} ; $Q_t = G_{cg} H_{lg} + G_{cH_2} H_{lH_2}$, kJ cycle^{-1} , where p_i is average rated pressure, MPa; V_s = working volume of the cylinder, m^3 ; G_{cg} and G_{cH_2} = the cycle quantities of gasoline and hydrogen entering the engine cylinder, kg cycle^{-1} ; H_{lg} and H_{lH_2} = the low heat of combustion of gasoline and hydrogen, kJ kg^{-1} .

The cycle quantities of gasoline and hydrogen are defined by the expressions

$$G_{cg} = \frac{G_g}{30 n i}, \text{ kg cycle}^{-1}; G_{cH_2} = \frac{G_{H_2}}{30 n i}, \text{ kg cycle}^{-1} \quad (8)$$

where G_g and G_{H_2} are the consumption rates of gasoline and hydrogen, kg h^{-1} , n = rotation frequency of the crankshaft, min^{-1} ; i = the number of cylinders.

The average rated pressure is defined by processing the experimentally obtained rated diagram.

If, in the analysis of the working cycle of the internal combustion engine, the average rated pressure p_i has not been defined, to define the rated efficiency the following expression can be used

$$\eta_i = \frac{3600 N_i}{G_g H_{lg} + G_{H_2} H_{lH_2}} \quad (9)$$

where N_i is the rated power of the engine, kW; G_g and G_{H_2} = the consumption rate of gasoline and hydrogen, kg h^{-1} and H_{lg} and H_{lH_2} = the lower heat of combustion of gasoline and hydrogen, kJ kg^{-1} .

The rated power can be defined by the dependence

$$N_i = N_e + N_{\text{mech}} \quad (10)$$

where N_e is the effective horsepower, kW and N_{mech} = the power consumed to overcome the losses of the engine, kW.

One of the basic characteristics of internal combustion engine working with liquid fuel is the rated specific fuel consumption g_i , kg kWh^{-1} .

The factor rated specific heat consumption q_i is analogous to it for internal combustion engines working with supplementary hydrogen to the fuel–air mixture:

$$q_i = \frac{G_g H_{lg} + G_{H_2} H_{lH_2}}{N_i}, \text{ kJ kWh}^{-1} \quad (11)$$

where G_g and G_{H_2} are the consumption rates of gasoline and hydrogen, kg h^{-1} ; H_{lg} and H_{lH_2} = the lower heat of

combustion of gasoline and hydrogen, kJ kg^{-1} and $N_i =$ the rated power, kW.

The effective efficiency η_e and the effective specific consumption of heat q_e are defined by analogous to η_i and q_i dependences, where the rated power N_i is substituted in the expressions for η_i and q_i with the effective power.

To evaluate the economy of gasoline burning supplementary hydrogen to the gasoline-air mixture, the specific effective consumption of heat q_e is turned into an arbitrary fuel consumption but calculated for gasoline:

$$g_{e_s} = \frac{q_e}{H_{lg}}, \text{ kg kWh}^{-1} \quad (12)$$

where q_e is the effective heat consumption when the internal combustion engine burning supplementary hydrogen, kJ kWh^{-1} and H_{lg} = the lower combustion heat of gasoline, kJ kg^{-1} .

When studying the characteristics of the engine with supplementary hydrogen to the gasoline-air mixture the following working conditions should be considered: at a constant given air ratio λ ; at a constant percentage relation of hydrogen to the fuel-hydrogen and gasoline; at constant hydrogen consumption to the gasoline-air mixture.

The realization of these conditions in the process of studying the engines is connected with definite difficulties to define the values of the initial quantities.

When λ is known, graphically one can define the values of the initial quantities: consumption rates of gasoline; consumption rate of hydrogen and consumption rate of air according to the conditions of testing for every point of the characteristics.

Operation of the engine with constant air ratio λ . When a gasoline engine burns supplementary hydrogen, the air ratio is defined by the formula (6).

With $\lambda = \text{constant}$, equation (6) becomes

$$\lambda = \frac{G_{\text{air5}}}{14.8 G_g + 34.5 G_{\text{H}_2}} = \text{const.} \quad (13)$$

as $l_{\text{th}_g} = 14.8 \text{ kg kg}^{-1}$ and $l_{\text{th}_{\text{H}_2}} = 34.5 \text{ kg kg}^{-1}$, i.e. an equation with three variables: G_g , G_{H_2} and G_{air} .

The air consumption rate is defined with the help of a sprayer according to the formula

$$G_{\text{air}} = 12.52 \times 10^{-3} d^2 (\rho_{\text{air}} \Delta H)^{1/2}, \text{ kg h}^{-1}. \quad (14)$$

where d is the diameter of the sprayer, mm; ρ_{air} = the density of the air, kg m^{-3} and ΔH = the reading of the differential manometer, mm H_2O . When $\rho_{\text{air}} = \text{const}$, it follows that $G_{\text{air}} = f(\Delta H)$.

The consumption rate of gasoline is defined by the formula

$$G_g = \frac{3.6 V_{\text{exp}} \rho_g}{t_{\text{exp}}} \quad (15)$$

where V_{exp} is the volume of the measuring flask, ml; ρ_g = the fuel density, g cm^{-3} and t_{exp} = the time of the consumption of the fuel from the measuring flask, s. Hence $G_g = f(t_{\text{exp}})$.

The consumption rate of hydrogen is defined by the formula

$$G_{\text{H}_2} = 10^{-3} Q_{\text{H}_2} k \rho_{\text{H}_2}, \text{ kg h}^{-1} \quad (16)$$

where Q_{H_2} is the reading on the rotometer, 1 h^{-1} ; k_ρ = the correction coefficient, giving the difference in the air density and that of hydrogen (the rotometers are usually tared for air consumption) and ρ_{H_2} = the hydrogen density, kg m^{-3} .

From equation (16) it follows that $G_{\text{H}_2} = f(Q_{\text{H}_2})$.

To solve equation (13), the nomogram shown in Fig. 32 is used.

When using a sprayer the height of the column of the water differential manometer is comparatively small so, for more precise reading, a micromanometer is used. The nomogram B converts the reading of the micromanometer into mm H_2O , k_1 , k_2 and k_3 being coefficients, reading the incline of the scale.

The usage of the nomogram is carried out in the following sequence: with the help of the nomogram A the density of the air ρ_{air} is defined at given pressure of the air ρ_{air} and air temperature T_{air} .

The variable ΔH , mm H_2O from the nomogram B, is defined through read on the spirit column. The air consumption G_{air} is defined with the help of the nomogram B and the density by the nomogram A.

The nomogram B has been built on a logarithmic scale to obtain the linear dependence between ΔH and G_{air} , which is parabolic in Cartesian coordinates.

From the nomogram D the consumption rate of hydrogen is defined as a result of the defined consumption rate of air and time read for the consumption of a certain volume of fuel with a given air ratio λ .

The nomogram E is the consumption rate of hydrogen G_{H_2} read on the rotometer Q_{H_2} . The consumption rate Q_{H_2} read is set with the rotometer and work of the engine with the desired air ratio is accomplished.

Operation at constant percentage relation of hydrogen to the total fuel, hydrogen and gasoline (Fig. 33). If we denote the percentage relation of hydrogen-fuel with a , then

$$Q = \frac{G_{\text{H}_2}}{G_g + G_{\text{H}_2}} 100\%. \quad (17)$$

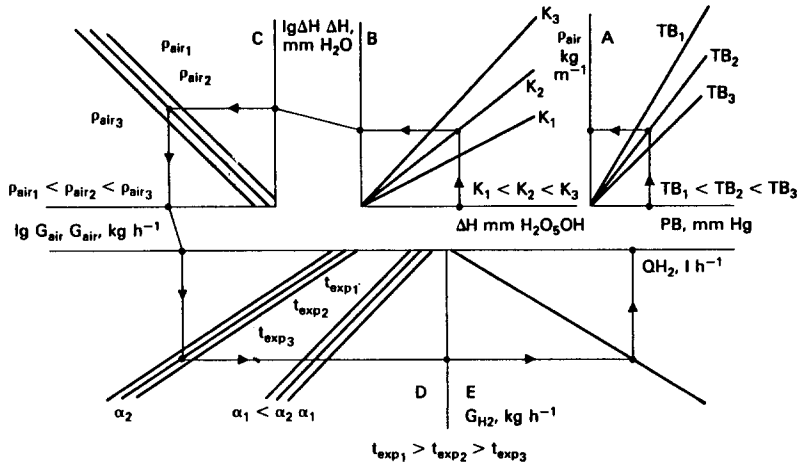


Fig. 32. A nomogram to define the consumption rate of gasoline, hydrogen and air when the engine operates at a constant air ratio.

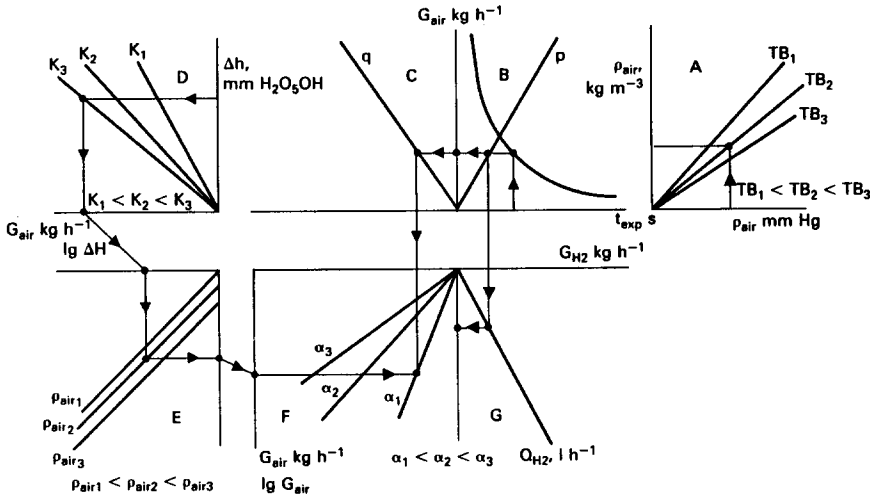


Fig. 33. A nomogram to define the consumption rate of gasoline, hydrogen and air when the engine operates at a constant percentage content of hydrogen to the total fuel of gasoline and hydrogen.

From (17) we express $G_{H_2} = a_1 G_g$.

Then equation (6) becomes

$$\lambda = \frac{G_{air}}{G_g l_{th_g} + a_1 \bar{G}_g l_{th_{H_2}}} \quad (18)$$

Equation (18) is with three unknown quantities. To fulfil equation (17), λ and Q_{H_2} are defined with the help of the nomogram.

Operation with the nomogram is carried out in the following sequence. The air density ρ_{air} is defined by nomogram A. Gasoline consumption G_g at measured

time of the experiment t_{exp} is defined by nomogram B. The dependence given by the straight line p is built in the nomogram C. At a given consumption of gasoline G_g the consumption rate of hydrogen is defined and transformed in a reading on the rotometer Q_{H_2} . The straight line q of the nomogram C is an equation of the denominator of eq. (18), i.e. the value of $G_g l_{th_g} + a_1 \bar{G}_g l_{th_{H_2}}$ is obtained from C.

Through nomogram D the readings of the spirit column are transformed into readings of a water column, and through nomogram E with the obtained value

of ΔH and ρ_{air} the air consumption is obtained. Through nomogram F at given G_{air} and $G_g l_{th_g} + a_1 G_g l_{th_{H_2}}$ the value of the air to fuel ratio is defined.

For the case when constant consumption of hydrogen to the gasoline-air mixture is kept, the desired nomogram is built analogically.

When the internal combustion engine burns supplementary hydrogen the increase of the relative quantity of hydrogen in the fuel-air mixture can bring about great degrees of leaning of the mixture ($\lambda = 4$ to 5) at very low levels of emission of all noxious components.

Figure 34 shows the dependence of the alteration of the relative quantity of hydrogen in the gasoline-air mixture on the degree of its leaning.

This dependence has been obtained for a single cylinder engine and has been checked for the engine of VAZ-2101 and is a way of qualitative control of the engine by changing the content of the fuel-air mixture.

Such control reveals great possibilities to improve the toxic and economic characteristics of gasoline automobile engines.

As seen in Fig. 35, the 5% supplementary hydrogen allows us to maintain the maximum power of the engine at 30% lower gasoline consumption. This is essential from the view-point of economy of oil fuels (8).

Figure 36 shows a comparison of the levels of the toxic characteristics when the engine of VAZ-2101 works according to load characteristic. The load characteristic is taken for the most typical velocity conditions of operating the automobile in town and is obtained for three cases of engine operation: gasoline and hydrogen and realization of a qualitative control (curves 1); gasoline and hydrogen and control of qualitative (throttle) control (curves 2) and operation only with gasoline (curves 3).

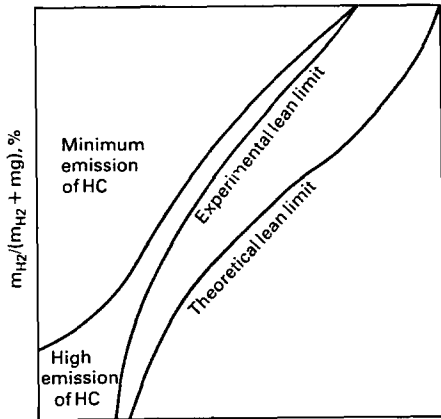


Fig. 34. Alteration of the relative quantity of hydrogen in the gasoline-air mixture according to the air ratio λ .

The alteration of the effective efficiency, the air ratio and the percentage content of H_2 in mass at the same working conditions are shown in Fig. 37. When the engine of VAZ-2101 works according to load characteristic the power changes at the expense of gasoline consumption at practically constant hydrogen consumption (Figs 36 and 37) [8]. For such a method of control within the boundaries of the load characteristic the air ratio a changes from $a = 1.024$ at maximum power to $a = 4$ at idle run and the percentage relation of hydrogen, from 5 to 47%. Studies have shown that the working process in the whole interval of modification of the content of the fuel-air mixture is stable if the ignition advance angle is optimal.

Figures 38-40 show the modification of the typical

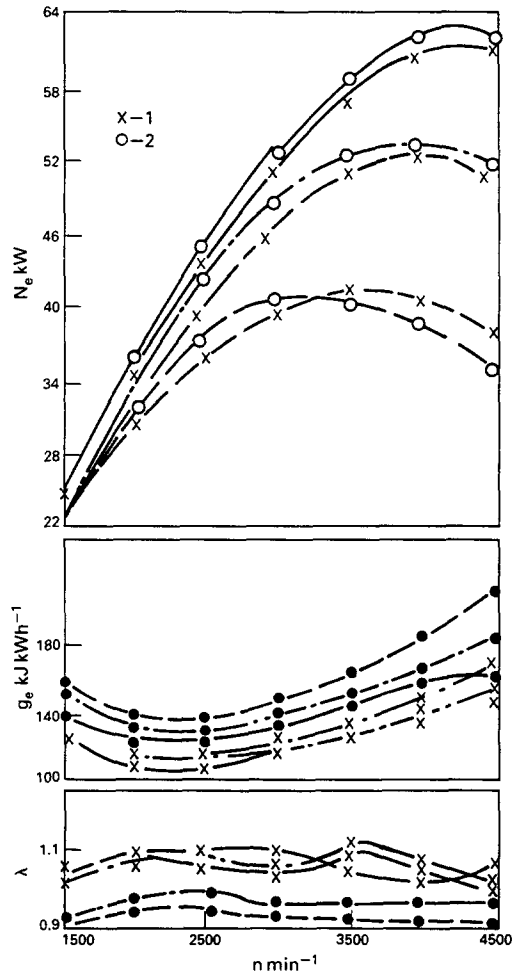


Fig. 35. Velocity characteristic of engine GAZ-24 working with gasoline (curve 1) and 5% supplementary hydrogen (curves 2).

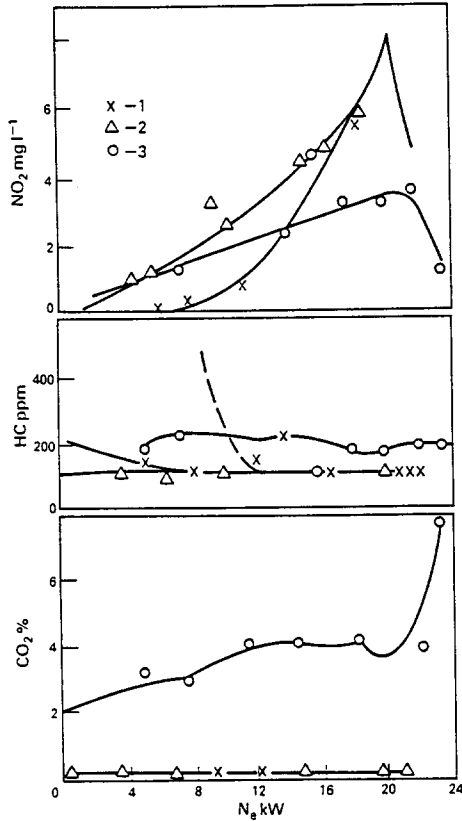


Fig. 36. Alteration of CO, CH and NO_x according to the loading of the engine of VAZ-2101.

parameters of the engine of VAZ-2103 burning supplementary hydrogen [22].

The air ratio a is defined by dependence (6). When the engine works according to the control characteristic with the increase of supplementary hydrogen, the range of inflammation of the mixture expands and gasoline consumption is lowered. At 0.18 kg h⁻¹ hydrogen consumption, the decrease is from 9 to 12% and at a consumption of 0.29 kg h⁻¹ the decrease is from 14.3 to 20% (Fig. 38).

The content of NO in the exhaust gases increases with the increase of hydrogen consumption. To lower the content of NO, the possibility for the engine to work at air ratio $a = 1.4$ to 1.5 should be studied. The concentration of CO is diminished with the increase of supplementary hydrogen approximately by 7% in rich mixtures and by 35% in lean mixtures. With supplementary hydrogen the total content of CH in the exhaust gases decreases approximately with 20 to 40% in rich mixtures, and in lean mixtures it increases with 15 to 45%. The effective power of the

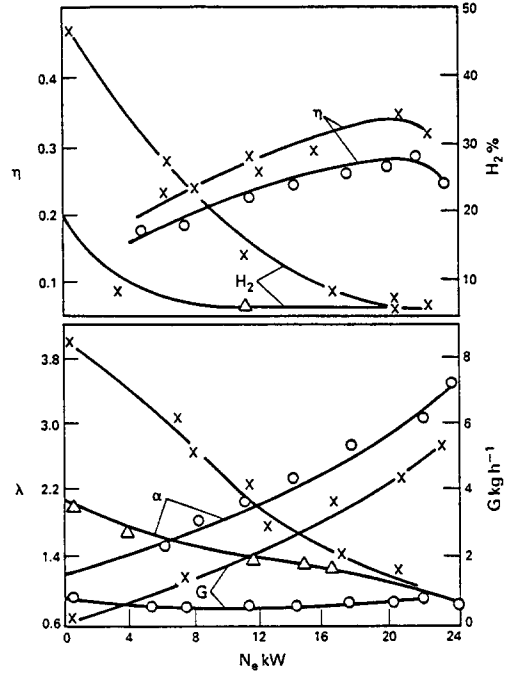


Fig. 37. Modification of the effective efficiency, the air ratio a and the percentage content of the hydrogen according to the load of the engine of VAZ-2101.

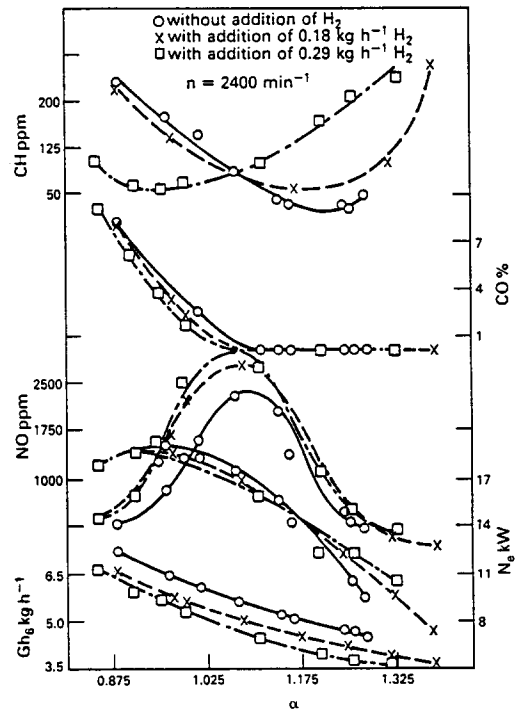


Fig. 38. Control characteristic of the content of the fuel-air mixture when the engine of VAZ-2103 burns supplementary hydrogen.

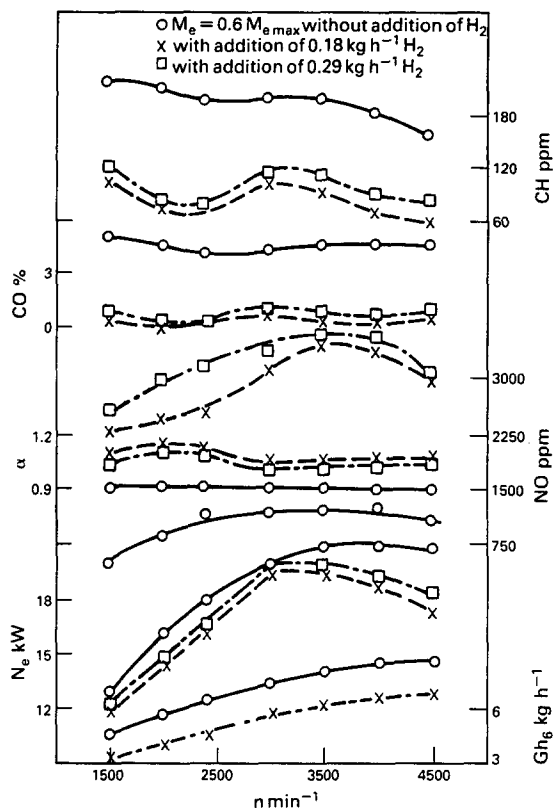


Fig. 39. Velocity characteristic of the engine of VAZ-2103 burning supplementary hydrogen.

engine working with supplementary hydrogen is lower on the average by 3% at 0.18 kg h^{-1} and by 4% at 0.29 kg h^{-1} . This is due to the much lower density of hydrogen compared to that of gasoline.

When the engine works according to velocity characteristic (Fig. 39) the weight relation hydrogen-gasoline changes in the boundaries of 4.2 to 8.2% and 2.63 to 5.47% at 0.18 and 0.29 kg h^{-1} hydrogen consumption, respectively. The economy of gasoline for both cases of hydrogen consumption is in the range of 20 to 30% and the decrease of CO is in the range of 77 to 97%, the greatest decrease of the effective power being 12%. The total content of CH decreases at the average with 45 to 64% for both cases of hydrogen consumption, at hydrogen consumption of 0.29 kg h^{-1} the decrease being less. The concentration of NO with supplementary hydrogen increases, reaching 71%.

Gasoline consumption at load characteristic (Fig. 40) decreases at the average with 23 to 25%, and the relation of hydrogen-gasoline changes in the range of 2.34 to 5.84% and from 3.8 to 10.21%, respectively at 0.18 and 0.29 kg h^{-1} hydrogen consumption. The concentration

of CO decreases with supplementary hydrogen with 23 to 96%. When the engine works with supplementary hydrogen the concentration of NO increases and reaches 70% at a hydrogen consumption of 0.18 kg h^{-1} and 74% at a hydrogen consumption of 0.29 kg h^{-1} . The total content of CH decreases with 15 to 64%, the decrease being greater at a hydrogen consumption of 0.18 kg h^{-1} .

The decrease of the total content of NO in the exhaust gases when the internal combustion engines work with supplementary hydrogen is achieved by recirculation of the exhaust gases or by supplementary water or vapor.

The modification of the characteristics of the engine of VAZ-2103 with supplementary water to the gasoline-hydrogen-air mixture is shown in Fig. 41. The water consumption in defining the characteristic is constant and is 1.76 kg h^{-1} . Hydrogen consumption is kept constant, 0.33 kg h^{-1} . The percentage content of water, related to gasoline in the fuel-air mixture, changes in the range of 20 to 50%.

From the experiments it has been established that with the increase of the air ratio α the difference in the

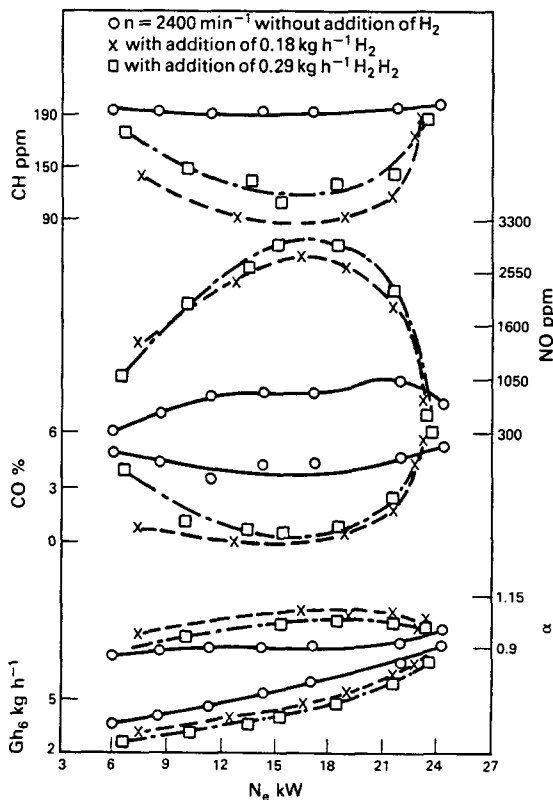


Fig. 40. The load characteristic of the engine of VAZ-2103 burning supplementary hydrogen.

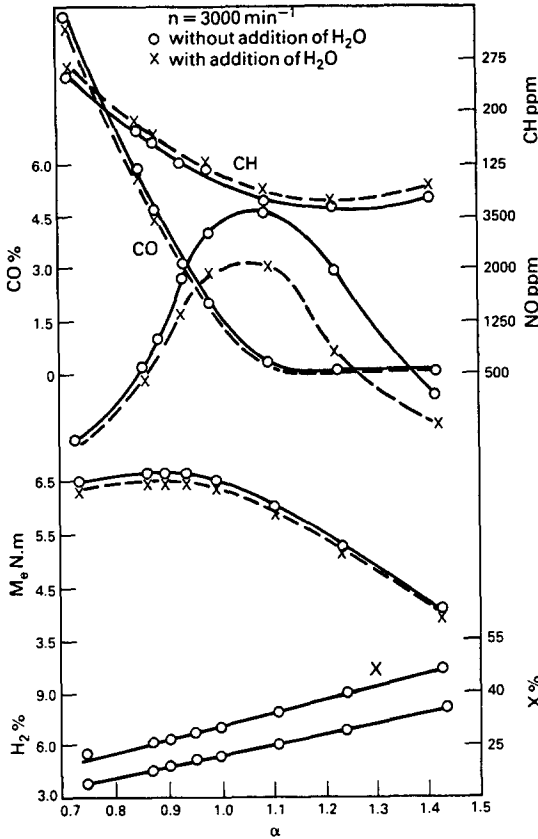


Fig. 41. Control characteristic according to content of the fuel-air mixture when the engine of VAZ-2103 burns supplementary hydrogen and water.

content of NO in the exhaust gases increases too, in the cases when water is fed or not. The decrease of NO at air ratio $a = 0.86$ is 12.4% and at $\lambda = 1.47$ it is 47%. The greater degree of decrease of NO with the increase of a is explained with the decrease of the combustion temperature of leaner mixtures and increase of the relative quantity of water.

The percentage content of hydrogen is increased with the increase of a . The percentage content of hydrogen is in the range 4–9%. Supplementary water has little effect on the modification of the effective characteristics of the engine.

With supplementary water to rich mixtures the effective power decreases with about 1.5% and for lean mixtures with about 25%.

The amount of CO in exhaust gases with supplementary water decreases comparatively little and the decrease is in the range of 5 to 10%.

The total content of CH with supplementary water increases slightly, with about 6%.

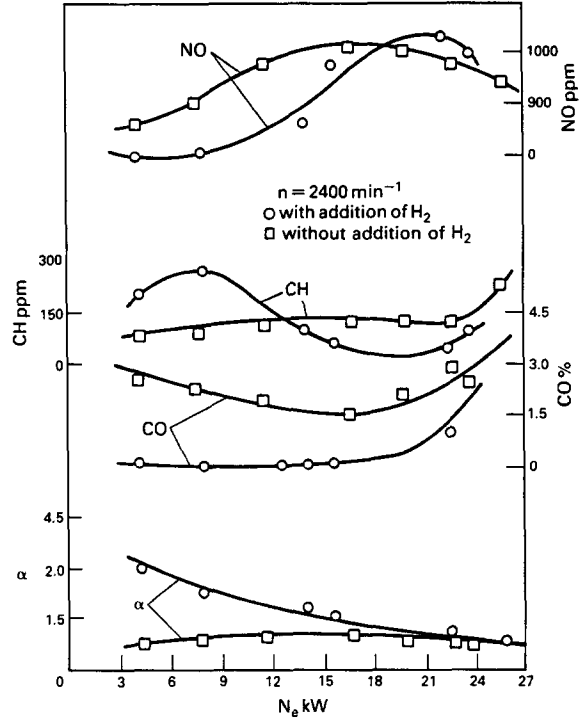


Fig. 42. Load characteristic of the engine of VAZ-2103.

Figures 42 and 43 show the load characteristics when the engine of VAZ-2103 burns supplementary hydrogen to the gasoline-air mixture and air consumption through the carburetor. The consumption of hydrogen and gasoline has been changed in the process of study [23].

With supplementary hydrogen to the gasoline-air mixture the air ratio changes in the range of $\lambda = 0.88$ at maximum load, $\lambda = 3.02$ at small loads and $\lambda = 5.3$ at idle run while when working only with gasoline the change of λ is in the range of $\lambda = 0.88$ to 1.05. The percentage content of hydrogen is 3% at maximum load and 28% at minimum load, respectively. The content of CO in the exhaust gases in the whole interval of loading is less than that when the engine burning gasoline and at air ratio $\lambda > 1.4$ CO tends to zero.

The total content of CH in the exhaust gases at medium and high loads is lower than that when the engine works with gasoline and is approximately 60%, but at low loads where the fuel mixture is very lean ($\lambda = 2$ to 3), the content of CH is higher with about 25%. The increase of CH in the very lean mixtures is due to the slow and incomplete combustion of the fuel mixture.

The content of NO in the exhaust gases decreases with the increase of the air ratio λ above 1.1, at $\lambda = 2.3$ being zero.

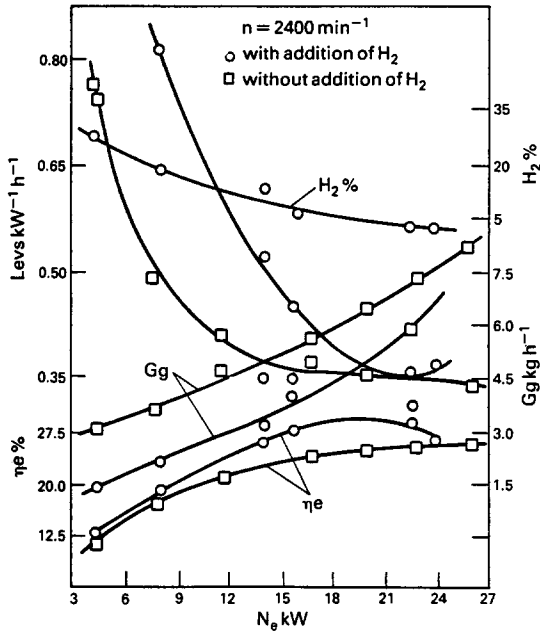


Fig. 43. Load characteristic of the engine of VAZ-2103.

The wide range of controlling the content of the fuel mixture leads to a decrease of gasoline consumption in comparison with the operation of the engine only with gasoline, the decrease being 10% at maximum load and 60% at lower loads. The fuel economy of the engine burning supplementary hydrogen grows at the average by 10 to 16% in the whole interval of loading.

For example, if the engine is to work with an effective power of $N_e = 20$ kW with supplementary hydrogen heat consumption of $244068\ kJ\ h^{-1}$ is necessary and without supplementary hydrogen, $288000\ kJ\ h^{-1}$. Hence heat consumption is greater by 18%. Economical work is related to the engine work with air ratio of $\lambda > 1.1$. In the example given $\lambda = 1.4$ and the percentage content of hydrogen in the mixture is 7%.

Figure 43 gives the value to obtain power of 1 kW in an hour. When the engine burns supplementary hydrogen the price is higher at the average by 5 to 10% at high loadings and by about 30 to 50% at low loadings.

From the studies carried out it has been established that with supplementary hydrogen to the gasoline-air mixture we can expand the range of combustibility of the fuel-air mixture which helps the work of the engine with a leaner mixture; the total content of CH when the engine works by load and velocity characteristic is lowered at the average by 15 to 64%; the emission of the toxic substances CO and NO is lowered to almost zero at

$\lambda > 1.4$ and $\lambda > 2.3$ respectively; the effective efficiency of the engine is increased at the average by 8–16%; gasoline consumption is lowered by about 10 to 60% according to the engine loading.

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