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# SOME ASPECTS OF HYDROGEN APPLICATION AS A SUPPLEMENTARY FUEL TO THE FUEL–AIR MIXTURE FOR INTERNAL COMBUSTION ENGINES

T. I. PETKOV and K. N. BARZEV

Technical University "A. Kanchev", Rousse, Bulgaria

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**Abstract**—The paper discusses some of the energy-ecological aspects of the increase of production and usage of internal combustion engines. The analysis of the research shows that oil fuels, which are getting exhausted, and which are the main source of air pollution, can be replaced fully or partially by hydrogen, used as a fuel. We have shown the advantages of hydrogen used as a supplementary fuel to the oil fuels, we have shown methods of adding hydrogen to the oil fuels. We have given the basic mathematical relationships to define the coefficients of the internal combustion engines when working with an addition of hydrogen, necessary to design the systems of operation of the engines with hydrogen as a supplementary fuel. We have also studied and analyzed methods to lower the nitrogen oxides when a gasoline engine works with a hydrogen addition.

## NOMENCLATURE

| | |
|---|---|
| $Q$ | Introduced heat when working with gasoline and hydrogen |
| $Q_g$ | Introduced heat when working only with gasoline |
| $\lambda$ | Excess air ratio |
| $H_2\%$ | Hydrogen mass concentration in hydrogen–gasoline mixture |
| $G_{H_2}$, $G_{l.f}$, $G_{air}$ | Consumptions of hydrogen, liquid fuel and air |
| $l_{th_{l.f}}$, $l_{th_{H2}}$ | Amounts of air theoretically needed for the combustion of 1 kg liquid fuel and 1 kg hydrogen |
| $\eta_i$, $\eta_e$ | Indicated and brake thermal efficiency |
| $P_i$ | Mean indicated pressure |
| $H_{l_{l.f}}$, $H_{l_{H2}}$ | Lower heating values of liquid fuel and hydrogen |
| $N_i$, $N_e$ | Indicated and brake power |
| $q_i$, $q_e$ | Specific indicated and brake consumption of heat |
| $g_{e_c}$ | Conditional specific effective fuel consumption |
| $K_w$ | Dry to wet correction factor |
| $X_{dry\ bas.}$, $X_{wet\ bas.}$ | Exhaust species volume concentration measured on a dry basis or on a wet basis |
| $W$ | Specific humidity |
| $n$ | Engine speed |
| $\varkappa$ | Percentage content of water in the fuel-water mixture |

## INTRODUCTION

According to scientific prognosis maximum consumption of petroleum is expected in about 2005. While for the period of 1972–1982 internal combustion engines have spent 52% of the products of petroleum, somewhere about 2020 they are expected to spend about 82% [1]. Internal combustion engines provide 85% of the energy needed by mankind [2] and it is supposed that in populated areas their share of air pollution reaches up to 70% [3]. It is supposed that for a period of 60–80 years they will remain the basic converter of heat energy from the combustion of fuels in mechanical work. Bearing in mind the rates of increase of engine building, one can believe their development and improvement will be of consequence to petroleum exhaustion. A great reserve for economy of the oil fuels used in internal combustion engines is their partial or full substitution for fuels of another origin, which should have such physical–chemical properties which do not require radical changes in the engine construction, in the combustion equipment and in the storing equipment on board. One of the most perspective ways of substituting liquid oil fuels is the usage of hydrogen both as a basic fuel or as a supplementary fuel to the liquid oil fuels. It is expected that when hydrogen is produced in great quantities its price will not be very high and if the present tendencies of mineral fuel consumption keep the same, then the price of hydrogen obtained and the price of oil fuels will be the same [4]. In the usage of hydrogen as a fuel in all fields of human activity one should note that while fossil fuels are exhaustible and they pollute the environment, hydrogen as an energy carrier is practically inexhaustible and in its combustion the main toxic substances released are nitrogen oxides. Research shows that hydrogen can be used either as a main fuel for internal combustion engines or as a supplementary fuel to the oil fuels. The use of hydrogen as an addition requires smaller volume and weight of the storing container which is of considerable importance for the stages of using hydrogen as a fuel in internal combustion engines.

## THEORETICAL ASPECTS CONCERNING HYDROGEN'S SUPPLEMENTATION

Usage of hydrogen as an addition to oil fuels has an immense ecological effect and brings about considerable economy principally because of improvement of the conditions of the combustion process and provision of the possibility for the engines to work with a leaner air–fuel mixture with a hydrogen addition to the oil fuel. Figure 1 shows the alteration of the ratio of introduced heat when working with gasoline and hydrogen to the introduced heat when working only with gasoline and keeping air consumption and the excess air ratio constant. Therefore the improvement of the engine factors when adding hydrogen should not be explained with the increase of the introduced heat. The more so as with external mixture formation when supplementary hydrogen is increased, air consumption decreases, so does the introduced heat. That is why in the near future while the problems connected with hydrogen storing on board are being solved and until production and availability of hydrogen in great quantities are provided, the method of adding hydrogen to the oil fuel for internal combustion engines is an important stage in the research of complete usage of hydrogen as a main fuel in engine power plants.

Hydrogen has some unique properties because of which it is a better fuel than synthetic and fossil fuels as it can be converted in other forms of energy with a higher power coefficient [5]. Hydrogen which will play the role of an energy carrier in the hydrogen energy system offered is a fuel with specific properties and characteristics which the fuels lack. Besides, it is compatible with the environment and has more favourable combustion characteristics [6]. In organizing the operation of internal combustion engines with hydrogen as an addition to

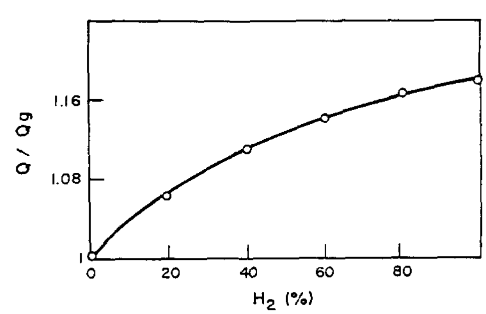


Fig. 1. Dependence of hydrogen addition of introduced heat.

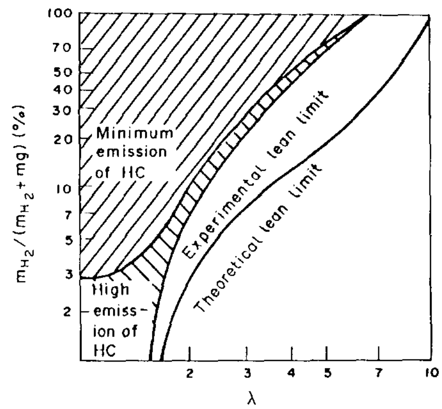


Fig. 2. Dependence of a gasoline–hydrogen–air mixture lean limit on the relative amount of hydrogen.

the air–fuel mixture, the following methods of hydrogen metering are used for the time being:

— constant feeding of the same amount of hydrogen independent of the working conditions of the engines;
— alternating feeding of hydrogen to the air–fuel mixture.

In addition to these methods in which, when the internal combustion engines work with supplementary hydrogen to the fuel–air mixture the amount of hydrogen at various working conditions is different—for example, at idle the engines work with hydrogen only, at part load they work with simultaneous feeding of both hydrogen and liquid fuel and at maximum load they work only with liquid fuel [7].

When internal combustion engines work with hydrogen addition, the increase of the relative amount of hydrogen in the fuel–air mixture allows the engines to work with greater degrees of leaning of the mixture while the excess air ratio can reach 4–5 units [8]. As an example Fig. 2 shows the alteration of the relative amount of hydrogen in the gasoline–air mixture depending on the excess-air ratio $\lambda$ [9]. Using hydrogen as an addition to the fuel–air mixture, it is necessary to solve the problems concerning the design of combined fuel system of the engines providing optimal feeding for all operating conditions with liquid fuel, hydrogen and air. Feeding hydrogen to the fuel–air mixture can be carried out in several ways: feed into the inlet manifold (under low pressure); feed into the standard or modified for gaseous fuel carburettor; feed immediately next to the inlet valves of the engine; direct injection into the engine cylinders (under high pressure).

## CHARACTERISTICS OF THE ENGINE WITH HYDROGEN SUPPLEMENTATION

When designing, calculating and constructing the system for engines working with hydrogen as an additional fuel and when defining the engine factors, one should have in mind that the physico-chemical properties of gasoline and hydrogen are different. The physico-chemical properties of hydrogen and the specific requirements of its storing, and in some cases the possibility of obtaining it on board, define the requirements to the fuel and regulation systems when modifying internal combustion engines to work with hydrogen or hydrogen as an additional fuel.

When internal combustion engines work with supplementary hydrogen to the air–fuel mixture, having in mind the physico-chemical properties of hydrogen and liquid fuel, the main factors of the engines, both in designing new engines to work with a combined fuel of hydrogen and liquid fuel and in modifying existing engines to work with hydrogen as an addition, should be defined according to the following equations:

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

$$H_2\% = \frac{G_{H_2}}{G_{l.f.} + G_{H_2}} .100 \quad (1)$$

where $G_{l.f.}$ and $G_{H_2}$ are consumption per hour of liquid fuel and of hydrogen, kg $h^{-1}$.

The excess air ratio $\lambda$ is defined by an equation (2) at direct metering of the amount of hydrogen and liquid fuel fed to the engine per unit time.

$$\lambda = \frac{G_{air}}{G_{l.f.}\, l_{th_{l.f.}} + G_{H_2}\, l_{th_{H2}}} \quad (2)$$

where $G_{air}$ is the air consumption per hour,

$G_{lf}$—consumption of liquid fuel per hour,

$l_{th_{l.f}}$—the amount of air theoretically needed for the combustion of 1 kg liquid fuel;

$l_{th_{H2}}$—the amount of air theoretically needed for the combustion of 1 kg of hydrogen, kg/kg

$\eta_i$—indicated thermal efficiency—defined as the ratio of the amount of heat $\eta_i$ converted into indicated work in the engine cylinders to the total consumed amount of heat $Q_t$ to obtain this work, is defined by equation (3):

$$\eta_i = \frac{Q_i}{Q_t} = \frac{p_i\, V_s}{G_{c_{l.f}}\, H_{l_{l.f}} + G_{c_{H2}}\, H_{l_{H2}}} \quad (3)$$

where $p_i$ is the mean indicated pressure, MPa;

$V_s$—the swept volume of the cylinder, $m^3$;

$G_{c_{l.f}}$ and $G_{c_{H2}}$—the cycle amounts of liquid fuel and hydrogen fed into the cylinder of the engine, kg $cycle^{-1}$;

$H_{l_{l.f}}$ and $H_{l_{H2}}$—the lower heating values of liquid fuel and hydrogen, kJ $kg^{-1}$.

The cycle amounts of liquid fuel and hydrogen are defined by the equations:

$$G_{c_{l.f}} = G_{l.f}/30.n.i., \text{ kg/cycle};$$
$$G_{c_{H2}} = G_{H_2}/30.n.i, \text{ kg/cycle} \quad (4)$$

where $G_{l.f}$ and $G_{H_2}$ are the consumption of liquid fuel and hydrogen per hour,

$n$—engine speed,

$i$—the number of engine cylinders.

The indicated thermal efficiency $\eta_i$ can also be defined by the expression:

$$\eta_i = \frac{3600\, .\, N_i}{G_{l.f.}\, H_{l_{l.f}} + G_{H_2}\, H_{l_{H2}}} \quad (5)$$

where $N_i$ is the indicated power of the engine, kW;

$G_{l.f.}$ and $G_{H_2}$—the consumption of liquid fuel and hydrogen per hour, kg $h^{-1}$;

$H_{l_{l.f}}$ and $H_{l_{H2}}$—the lower heating values of the liquid fuel and of hydrogen, kJ $kg^{-1}$.

The indicated power is defined by the equation:

$$N_i = N_e - N_{mech.} \quad (6)$$

where $N_e$ is the brake power, kW;

$N_{mech.}$—the power consumed to cover the engine losses.

The specific indicated consumption of heat $q_i$ when the engines work with a mixture of liquid fuel and hydrogen is analogous to the specific indicated fuel consumption, kg $kW.h^{-1}$ when the engines work with liquid fuel:

$$q_i = \frac{G_{l.f.}\, H_{l_{l.f}} + G_{H_2}\, .\, H_{l_{H2}}}{N_i}, \text{ kJ kW h}^{-1} \quad (7)$$

where $G_{l.f.}$ and $G_{H_2}$ are the consumption of liquid fuel and hydrogen per hour, kg $h^{-1}$;

$H_{l_{l.f.}}$ and $H_{l_{H2}}$ the lower heating values of the liquid fuel and hydrogen, kJ $kg^{-1}$;

$N_i$—indicated power, kW.

The brake thermal efficiency $\eta_e$ and the specific brake consumption of heat are defined by relationships analogous to $\eta_i$ and $q_i$, the indicated power $N_i$ being substituted in the expressions for $\eta_i$ and $q_i$ with the effective power $N_e$.

To evaluate the liquid fuel economy when using additional hydrogen to the air–fuel mixture the specific brake consumption of heat $q_e$ turns into a conditional fuel consumption, but recalculated for liquid fuel:

$$g_{e_c} = \frac{q_e}{H_{l_{l.f.}}}, \text{ kg kWh}^{-1} \quad (8)$$

where $q_e$ is the brake consumption of heat when the engines work with supplementary hydrogen, kJ $kWh^{-1}$;

$H_{l_{l.f.}}$—the lower heating value of the liquid fuel, kJ $kg^{-1}$.

If in studying and defining the chemical substances in the exhaust gases when the engines work with supplementary hydrogen the measured concentrations are on a dry basis, then they are corrected up to actual concentrations in wet exhaust gases according to the equation:

$$X_{wet\ bas.},\ \% = k_W \cdot X_{dry\ bas.},\ \% \quad (9)$$

where $X_{\text{wet bas.}}$ is the exhaust species volume concentration on a wet basis;
$X_{\text{dry bas.}}$ is the exhaust species volume concentration measured on a dry basis;
$k_W$—dry to wet correction factor, showing the presence of water vapour in the exhaust gases due to humidity of the intake air, of the hydrogen in the liquid fuel, of the hydrogen's addition and of water, additionally fed to the air–fuel mixture.

The correction factor $k_W$ is defined by equation (10) [10]:

$$K_W = \frac{1}{1 + ([CO] + [CO_2]).\, [5.\,96\frac{g_c}{g_H} + \frac{5.96.\, G_{H_2}}{g_c\, G_{l.f}} + \frac{0.67}{g_c . G_{l.f.}}(10^{-3}.\, W.\, G_{air} + G_{H_2O})]} \quad (10)$$

where [CO] and $[CO_2]$ are the share of carbon monoxide and carbon dioxide in the exhaust gases;
$g_H$ and $g_c$—the share of hydrogen and carbon in the fuel;
$G_{H_2}$ and $G_{l.f.}$—the consumption of hydrogen and liquid fuel per hour,
$W$—specific humidity of the intake air,
$G_{air}$ and $G_{H_2O}$—the consumption of air and water or steam additionally fed to the air–fuel mixture, kg $h^{-1}$.

When the engines work with supplementary hydrogen to the air–fuel mixture, to evaluate the results obtained in defining nitrogen oxides when studying the work of the engines at various atmospheric conditions the mass emissions of $NO_x$ are corrected by the correction factor $k_{NO}$ [11].

The correction factor $k_{NO}$ is defined by the empirical equation deduced mainly for engines working with liquid fuel:

$$K_{NO} = 0.634 + 0.04582W - 0.0010897W^2$$

—for a gasoline engine

$$K_{NO} = 1 + 7.A\,(W - 10.714) + 1.8B\,(t - 29.444)$$

—for a diesel engine,
where $W$ is the specific air humidity, g $kg^{-1}$;
$t$—the temperature of the intake air, °C.

## ENGINE PERFORMANCE WITH HYDROGEN SUPPLEMENTATION

The research carried out [8] and the analysis of the results obtained when the engines work with supplementary hydrogen show that the toxic substances like carbon monoxide, hydrocarbons, aldehydes etc. can be reduced to a considerable degree at the same time effecting economy of liquid fuel. On the other hand, because of the better conditions for the mixture formation and the combustion characteristics of the air–fuel mixture, nitrogen oxides increase.

From the research carried out concerning the changes of the nitrogen oxides $NO_x$ [12] shown in Fig. 3 one can see that when the engine works with supplementary hydrogen to the gasoline–air mixture or only with hydrogen the content of $NO_x$ is higher than when working only with gasoline. Bearing in mind that in future the introduced standards limit more and more the amount of nitrogen oxides in the exhaust gases of internal combustion engines, then every suggestion bringing about their reduction is of a great practical importance. Besides through constructive modifications of the feeding, combustion and exhaust systems of the engine working with an additional hydrogen, the amount of nitrogen oxides can be reduced by altering the ignition timing (in engines with external mixture formation) or the fuel injection timing (in engines with internal mixture formation), by feeding supplementary quantity of water, by exhaust gas recirculation or by lowering the temperature of the intake air–fuel mixture.

To study the possibilities of reducing nitrogen oxides when working with an internal combustion engine using supplementary hydrogen to the air–fuel mixture, a study has been carried out of a four stroke gasoline engine with working volume of 1.45 l, compression ratio 8.8, bore 86 mm, stroke 80 mm, while with the change of the ignition timing, an additional amount of water is being

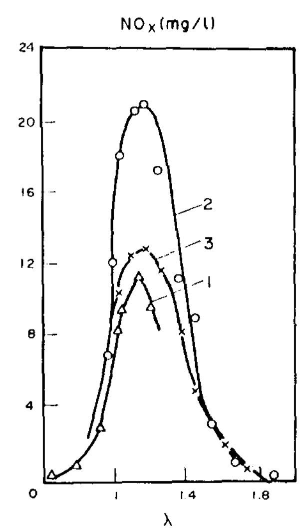


Fig. 3. Amount of $NO_x$ in the exhaust gases versus the excess air ratio $\lambda$: 1–gasoline; 2–hydrogen (VAZ 2101. $n$ = 2500 $min^{-1}$); gasoline and hydrogen (ZMZ–24, $n$ = 2500 $min^{-1}$).

fed to the hydrogen–gasoline mixture. A conventional carburettor of the engine has been used and the primary chamber has been adjusted to work with gasoline only and the secondary—with hydrogen. The additionally fed water to the carburettor diffusers is introduced with the help of jets, atomizers and a float chamber [13]. The percentage content of the water added to the air–fuel mixture is defined by equation (11):

$$\varkappa = \frac{G_{H_2O}}{G_{H_2O} + G_{gc}} . 100\% \qquad (11)$$

where $G_{H_2O}$ is water added, kg $h^{-1}$;
$G_{g_c}$—conditional gasoline (total amount of the gasoline in the fuel mixture and the gasoline corresponding in heat energy to the hydrogen added).

Control characteristics have been defined from the ignition timing with simultaneous feeding of water into the carburettor diffusers (Figs 4 and 5), while at the chosen constant engine speed ($n = 2400 \text{ min}^{-1}$) we have chosen 6% of additional hydrogen and excess air ratio of $\lambda = 1.2$. The results in Fig. 4 have been obtained for gasoline consumption per hour $G_{l.f.} = 3.74$ kg $h^{-1}$, and for Fig. 5—for gasoline consumption per hour $G_{l.f.} = 4.75$ kg $h^{-1}$. The volume concentration of nitric oxide NO is measured with the help of a ondispersive Ultraviolet (NDUV) analyser with an error of ± 1.5%. The volume concentration of carbon monoxide CO and the total content of hydrocarbons are measured with a Nondispersive Infrared (NDIR) analyser with an error of measurement up to 5% of the maximum range.

The analysis of the results obtained shows that with the decrease of the ignition timing up to 10° to the optimal one for the conditions studied the concentration of NO decreases by 45% (Fig. 4) and by 17% (Fig. 5), while the brake power of the engine decreases by 2.5% (Fig. 4) and by 5.2% (Fig. 5). When keeping the optimal

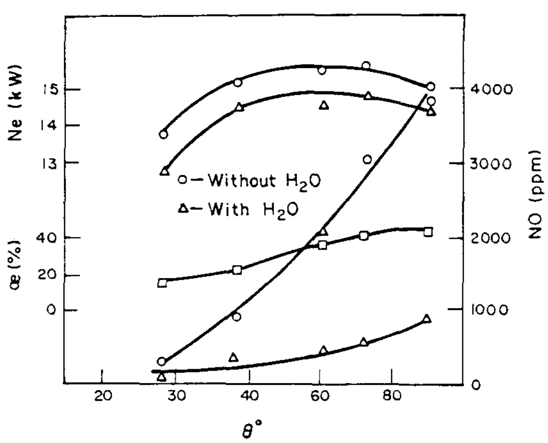


Fig. 4. The effect of ignition timing and water addition on NO and brake power.

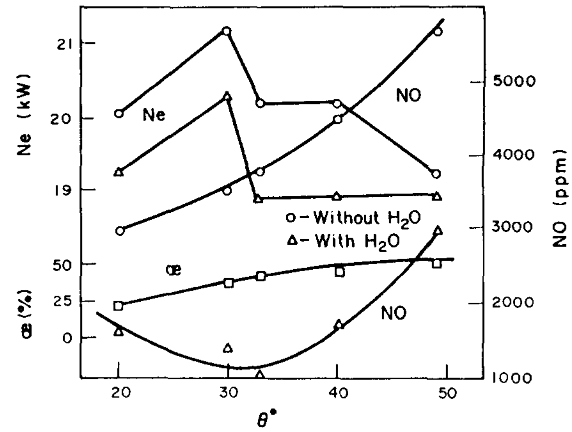


Fig. 5. The effect of ignition timing and water addition on NO and brake power.

ignition timing constant and adding water up to 38% the nitric oxide NO decreases respectively by 76% (Fig. 4) and 55% (Fig. 5) and the decease of the power is up to 5% (Fig. 4) and 4% (Fig. 5). From the studies carried out and the conditions discussed, it has been established that supplementary water does not considerably affect the amount of carbon monoxide CO and the total content of hydrocarbons HC and with the increase of the amount of gasoline and hydrogen in the fuel mixture the alteration of the ignition timing and of the supplementary water affect the alteration of NO levels.

## CONCLUSIONS

The introduction of an additional hydrogen to the gasoline–air mixture is of essential importance for the achievement of considerable ecological effect and of economy of liquid fuel. For the wide application of this method it is of a great importance to calculate, design and construct correctly a system considering the physico-chemical properties of the liquid fuel, hydrogen and air and providing optimal feeding with fresh charge all working conditions of the engine. To decrease the amount of nitrogen oxides in the exhaust gases when the engines work with an additional hydrogen to the oil fuels it is necessary to establish an adequate law of alteration of the ignition timing or fuel injection with simultaneous optimal feed of supplementary water to the air–fuel mixture.

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