THERMODYNAMIC CYCLE OF COMBUSTION ENGINE WITH HYDROGEN FUELLING

Zbigniew J. Sroka

Wrocław University of Technology
Institute of Machine Design and Operation
Łukasiewicza 7-9, 50-371 Wrocław, Poland
tel. +48 71 3204245, fax: +48 71 3477918
e-mail: zbigniew.sroka@pwr.wroc.pl

Abstract

Shortage of crude oil gives the reason to look for any alternative engine fuel. One of them is the hydrogen, which will be the most lean fuel between others. Knowledge of hydrogen as an engine fuel, its properties, production and storage problems were analyzed in this paper. At the end own hydrogen concept based on Fiat engine 900ccm was shown. Theoretical comparison between thermodynamic cycles for engine run on conventional petrol and hydrogen was done. Results have given the green light to future development.

2. Hydrogen as a engine fuel

Hydrogen could be an alternative engine fuel. It is the most popular chemical element in the world. It is the lightest and the most simply structure element. Hydrogen is odorless and colorless combustible gas. In each of the state (gas or liquid) hydrogen has got the lowest density, so
specific heat of hydrogen for weight unit is the highest. Hydrogen is characterized by high level of diffusion factor and because of this its molecules in gas state are the fastest. Fire range is 4 to 75% in mixture with the air. The combustion of hydrogen is environmental friendly. Water steam, heat and trace of NOx as well as HC and CO can be found in exhaust gas of hydrogen engine, but HC and CO they are rather effect of combustion of lubricating oil existed in chamber than because of hydrogen fueling. Hydrogen is not the source of energy like crude oil. It is a energy carrier.

2.1 Hydrogen – properties of fuel

Hydrogen differs in properties from conventional fuel. Some parameters are given in table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Hydrogen</th>
<th>Petrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorific value</td>
<td>MJ/kg</td>
<td>120</td>
<td>42 – 44</td>
</tr>
<tr>
<td></td>
<td>MJ/m³</td>
<td>10,77</td>
<td>~34500</td>
</tr>
<tr>
<td>Calorific value for stochiometric mixture</td>
<td>MJ/m³</td>
<td>2,97 – 3,17</td>
<td>3,50</td>
</tr>
<tr>
<td>Theoretical air need</td>
<td>kg/kg</td>
<td>36,6</td>
<td>~14,7</td>
</tr>
<tr>
<td>Octane number Test</td>
<td>-</td>
<td>-</td>
<td>91 - 98</td>
</tr>
<tr>
<td>Octane number Road</td>
<td>-</td>
<td>70</td>
<td>81 - 88</td>
</tr>
<tr>
<td>Density at 20 °C</td>
<td>kg/m³</td>
<td>0,0840</td>
<td>720 - 750</td>
</tr>
<tr>
<td></td>
<td>at 0 °C</td>
<td>0,0898</td>
<td>-</td>
</tr>
<tr>
<td>Explosion range % vol. in the air</td>
<td>% vol. in the air</td>
<td>4 - 75</td>
<td>1,16 - 7,00</td>
</tr>
<tr>
<td>Laminar combustion velocity</td>
<td>m/s</td>
<td>2,70 - 3,15</td>
<td>0,30 - 0,60</td>
</tr>
<tr>
<td>Temperature of self-ignition °C</td>
<td></td>
<td>585</td>
<td>480 - 550</td>
</tr>
<tr>
<td>Boiling point °C</td>
<td></td>
<td>- 253</td>
<td>35 - 215</td>
</tr>
<tr>
<td>Minimal ignition energy mJ</td>
<td></td>
<td>0,02</td>
<td>0,24</td>
</tr>
</tbody>
</table>

Hydrogen has got appropriate properties to use as a engine fuel in aprk ignition engine. There are:

**Wide burning range**

Hydrogen with air mixture can be burnet in the range 4-75%. It is advantage to use lean charge, what is important during start operating and in reduction of fuel consumption as well as combustion process an be more completed. Temperature of mixture is less than in petrol case, but the power is also low when lean hydrogen mixture supply engine.

**Low ignition energy**

Hydrogen needs only 0,02 mJ energy to ignite. It is ten times less than for petrol. On the one hand it is advantage – to help burning lean mixture but on the another hydrogen can be ignited from foe example hot walls of combustion chamber. It can cause combustion out of control.

**Short extinguish distance**

For hydrogen, extinguish distance is lower than for petrol. It means hydrogen flame can be very closed to chamber walls and it could be difficulty to extinguish it if necessary.

**High sel-ignition temperature**

Temperature of hydrogen self-ignition is relatively high. It is important when hydrogen-air mixture is compressed. This properties decides compression ratio in engine – higher causes higher one in this way.
Thermodynamic Cycle of Combustion Engine with Hydrogen Fuelling

High compression factor
Higher compression factor for hydrogen mixture than for petrol gives higher thermal efficiency. But, on the other hand high compression factor eliminates hydrogen from diesel engine application.

Fast flame velocity
Flame speed for hydrogen–air mixture is ten times higher than form petrol charge. It causes that hydrogen thermodynamic cycle much better fill work ideal cycle.

High diffusion
Hydrogen has got high diffusion. Its dissipation into air is big advantage of hydrogen as a fuel. First because of getting homogenous mixture and second because of safety reason.

Low density
Density of hydrogen is very low. There are two main disadvantages of this parameters: problem with hydrogen storage in the tank and low volumetric energy [8, 9].

2.2 Hydrogen combustion process

Combustion is a physical and chemical process based on rapid oxidization. For hydrogen, combustion in stheciometric mixture with oxygen and air is carry out as follow:

\[ 2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}. \]  
(1)

\begin{align*}
\text{number of moles } \text{H}_2 \text{ for completed combustion} & \quad 2 \text{ moles}, \\
\text{number of moles } \text{O}_2 \text{ for completed combustion} & \quad 1 \text{ mole}, \\
\text{number of moles } \text{N}_2 \text{ in the air} & \quad \text{O}_2 \times (79\% \text{ N}_2 \text{ in the air} / 21\% \text{ O}_2 \text{ in the air}) = \\
& \quad 1 \text{ mol } \text{O}_2 \times (79\% \text{ N}_2 \text{ w pow.} / 21\% \text{ O}_2 \text{ w pow.}) = 3,762 \text{ moles of } \text{N}_2, \\
\text{number of moles of the air} & \quad \text{mole } \text{O}_2 + \text{mole } \text{N}_2 = 1 + 3,762 = 4,762 \text{ moles of air}, \\
\text{mass } \text{O}_2 & \quad 1 \text{ mol } \text{O}_2 \times 32 \text{ g/mol} = 32 \text{ g}, \\
\text{mass } \text{N}_2 & \quad 3,762 \text{ mole } \text{N}_2 \times 28 \text{ g/mol} = 105,336 \text{ g}, \\
\text{mass } \text{H}_2 & \quad 2 \text{ mole } \text{H}_2 \times 2 \text{ g/mol} = 4 \text{ g}, \\
\text{mass of air} & \quad 32 \text{ g} + 105,336 \text{ g} = 137,336 \text{ g}. \\
\text{Stechiometric ratio air/fuel:} & \\
\text{mass} & \quad 137,336 \text{ g} / 4 \text{ g} = 34,336 : 1, \\
\text{volumetric (moles)} & \quad 4,762 / 2 = 2,4 : 1. \\
\end{align*}

Percentage of hydrogen filling in combustion chamber:

\[ \%\text{H}_2 = \text{vol. } \text{H}_2 / (\text{vol. air.} + \text{vol. } \text{H}_2) = 2 / (4,762 + 2) \approx 0,296 \approx 29,6\% \ [5, 6]. \]  
(2)

Calculation, mentioned above that low density of hydrogen causes low air access factor in stheciometric state – hydrogen fill 30% of chamber displacement against 2-4% for petrol only.

For outside preparation of mixture (carburetor type) power of hydrogen engine is less even 25% in comparison to petrol [4, 5, 6]. For direct injection (hydrogen split directed to chamber) power is higher up to 20%. Combustion process of hydrogen can be realized for very wide range of air/fuel factor (\( \lambda = 0,14 \div 10 \)). It gives completed burning process, easy start and supply with lean mixture. The results are lo temperature and reduction NOx trace level [4, 8].

In practice, hydrogen prototype engines are fueling with mixture for \( \lambda = 0,2 \div 5 \). It gives possibility controlling combustion process by hydrogen flow – not y air throttling.

Chemical process of hydrogen combustion can be presented as on equations (3-5).

\[ \text{H} + \text{O}_2 \rightarrow \text{O} + \text{OH}, \]  
(3)
\[ O + H_2 \rightarrow H + OH, \]  
\[ OH + H_2 \rightarrow H_2O + H. \]  

Reactions (3) and (4) give ramification of element chain. And equation (5) results with combustion products [4].

2.3. Thermal efficiency

Theoretical, thermal efficiency of spark ignition engine (Otto cycle) based on compression ratio and specific heat of fuel. When both of them are high thermal efficiency is growing, too. Compression ration is limited by knocking resistance of fuel. Lean hydrogen mixtures are better than petrol stochiometric and higher compression ratio can be applied.

Specific heat factor depends on fuel molecular structure and for simply structure is higher: for hydrogen \( \gamma = 1.4 \), for petrol \( \gamma = 1.1 \) [4, 5, 8].

2.4. Emission – toxic products of hydrogen combustion

Only one non-toxic product is result of hydrogen combustion in oxygen – water (6):

\[ 2H_2 + O_2 = 2H_2O. \]  

For burning in the air it an be found (7)

\[ H_2 + O_2 + N_2 = H_2O + N_2 + NO. \]  

\[ \text{Fig. 1. Emission of NO}_x\text{, for hydrogen engine [9]} \]

Nitric oxides are results of high temperature inside combustion chamber. It depends on air/fuel factor as well compression ratio, engine revolution, ignition delay.

3. Theoretical engine work cycle for hydrogen fueling

Thermodynamic cycle of combustion engine supply with hydrogen was calculated using standard theory and right formulas. Estimations were done for different air/fuel factor. Basic data was taken from Fiat Seicento engine with displacement of \( V_c = 899 \text{ ccm} \).
Diagrams, mentioned above show different examples of fueling. Engine work cycles were compared for petrol and hydrogen fuel and for $\lambda=0.5$, 1.0 and 3.0. Using too rich mixtures it could affect on durability because of temperature and high pressure (for petrol and $\lambda=1.0$ - $p_{\text{max}} = 6.9$ MPa, $T_{\text{max}} = 2502$ K; for hydrogen and $\lambda=1.0$ - $p_{\text{max}} = 7.99$ MPa, $T_{\text{max}} = 3437$ K; for hydrogen and $\lambda=0.5$ - $p_{\text{max}} = 12.5$ MPa, $T_{\text{max}} = 2575$ K). In these cases hydrogen engines have to be redesigned.

On the other hand lean mixture give poor engine parameters but low fuel consumption (for petrol and $\lambda=1.0$: $g_c = 309$ g/kWh, for hydrogen and $\lambda=3.0$: $g_c = 133$ g/kWh).

4. Summary

Petroleum recourses run out have given the reasons to find alternative fuel. One of them could be hydrogen. Before engine application some problems should be solved: production, storage, safety, materials etc.

According to analyze done in those project it can be found similarity between hydrogen engine with $\lambda=1.0$ to petrol engine with $\lambda=0.9$. Pressure of hydrogen charge is in this case higher of 0.42 MPa and there is calculated in strength of existing engine. Because of high temperature, cooling system should be redesigned.

The results of estimation show possibility to use hydrogen as a engine fuel, maybe first as a dual-fuel engine like LPG system.

Literatura


