Effects of the hydrogen addition on combustion in automotive diesel engine

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Abstract. Today, fossil fuel replacement and pollutant emissions reduction can be assured by hydrogen use at the automotive diesel engine, obtaining the engine energetic performance improving. The hydrogen has good combustion proprieties. The paper presents some experimental investigations results carried out at an automotive K9K engine diesel at 2000 rev/min speed and 70% load. They showed that hydrogen might be suitable partial substitute of diesel fuel. The hydrogen use assures the thermal efficiency increase due to combustion improvement through homogeneous air-hydrogen mixture rise. The experimental investigations results show that specific energetic consumption decreases with ~8%, the thermal efficiency increases from 31.9% to 34% due to combustion improvement at the hydrogen content increase. In the same time, due to combustion improvement HC and smoke emissions level decreases with 15% respectively 20%. NOx emissions level decreases with 11% comparative to diesel engine at for a 12% percent of substitute ratio of diesel fuel by hydrogen. At the higher percents of substitute ratio of diesel fuel by hydrogen the NOx emissions level increases due to temperature rise. A great advantage is the CO2 emission level decrease with 12% at the increase of percent of substitute ratio of diesel fuel by hydrogen.

1. Introduction

The effects of the pollutants and greenhouse gases emissions produced by car diesel engines through the combustion of fossil fuels on environmental is now restriction by sever lowed regulations which take into consideration the carbon dioxide, (CO₂), as green house gas and the unburned hydrocarbons, (HC), carbon monoxide, (CO), nitrous dioxide, (NOₓ), particles and smoke emissions decrease, [1]. The big car manufacturers are obliged to produce internal combustion engines that use fuels with low carbon in the molecular structure, [2].

In the 2015 Paris Agreement, signed by 200 countries at the United Nations Framework Convention on Climate Change, the measures for the limitation of the global medium temperature increasing and pollutants emissions concentration reduction are presented, [3]. In December 2019, the European Commission decided that until 2050 the EU will become greenhouse gas neutral by 2050 and the transport sector must reduce its pollutants emissions by 90% by 2050, [4].

All these regulations require new solutions and technologies and new fuels for the internal combustion engines in general and for diesel engines in special. Is clear that is imposing the replacement of the fossil fuels that contain carbon in their structure. From the alternative fuels studied,
the hydrogen can be taken into consideration because it assures the engine operation with lowest level of pollutant emissions and the best energetic performance, [5, 6, 7].

Hydrogen good combustion properties made it the cleanest fuel for internal combustion engine and a high thermal efficiency of combustion can be assured at its use, [8, 9]. There are three problems for the hydrogen use at the diesel engines: hydrogen production, hydrogen storage and hydrogen use. The paper takes in consideration only the hydrogen use at automotive diesel engines. Some hydrogen proprieties are recommended it as a good fuel for diesel engine. Therefore, the high diffusion velocity of hydrogen assures the rise of the mixture’s homogeneity. It has a high octane number being an optimum fuel for the spark ignition engines with high compression ratios but the high autoignition temperature and lower cetane number worse its autoignition properties, being necessary to use specific fuelling methods for its use at diesel engines. The hydrogen has wide flammability limits in air, [8], assuring the engine operation with lean mixtures and the engine cycle efficiency increase. Flame temperature at hydrogen combustion is higher and the nitrous oxides level increases, but through lean mixtures use the nitrous oxides concentration can be reduced significantly. Comparative to diesel fuel hydrogen has lower energy volumetric density which requires the use of an adequate fuelling system in order to maintain the standard engine power.

The experimental investigations results carried out on automotive diesel engine fuelled with hydrogen in addition at diesel fuel highlighted some effects of its combustion comparative to standard diesel. Thus, in general, at the increase of used hydrogen addition was observed:

- the maximum pressure and the maximum pressure rise rates lightly increase, [7, 8, 10];
- the engine thermal efficiency increase at the small and middle engine loads due to the improvement of combustion, [8, 9, 11, 12, 13] and the thermal efficiency slightly decrease at the engine loads because of the incomplete combustion of richer mixture, [16];
- the heat release maximum rate increases due to the higher combustion velocity of hydrogen comparative to diesel fuel, [7, 8, 11];
- the decrease of CO and HC emissions concentrations for small used hydrogen quantities, but at the increase of hydrogen quantity the combustion is incomplete and these emissions level increases, [7, 11];
- the reduction of the smoke emission due to improvement of the combustion process and decrease of the carbon content from the cyclic fuel dose, [7, 8];
- the NOx emissions level decrease for small hydrogen additions and increase for higher hydrogen additions, [7, 8, 14].

From this short study results the great advantages of the hydrogen use at the automotive diesel engines.

The objective of this paper is to study the effects of hydrogen use as addition to diesel fuel on the operation automotive diesel engine.

2. Experimental investigations

A supercharged K9K diesel engine was fuelled with diesel fuel and hydrogen at different energetic substitute ratios, for the operate regime of 70% engine loads at 2000 min⁻¹ speed.

The test bed presented in the figure 1 is adequate equipped; all the experimental instruments and equipment’s were calibrated.
1-hydrogen reservoir, 2 - Alicat Scientific MCR hydrogen flowmeter, 3 - hydrogen injector, 4- K9K diesel engine, 5-Dastek Unichip computer, 6- AVL data acquisition system (AVL Indimodul Card C1 acquisition board and AVL Indimodul 621), 7- dyno control cabinet, 8- Unichip electronic unit, 9- Schenck eddy current dyno, 10- AVL DiCom 4000 gas analyser and opacimeter, 11- engine air reservoir, 12- Krohne air flowmeter, 13- Optimass diesel fuel flowmeter, 14- diesel fuel reservoir.

**Figure 1.** Test bed schema.

The hydrogen is injected in the inlet manifold. The hydrogen injector is actuated from an unchip electronic unit (Dastek Unchip). The unichip unit controls the opening duration of the hydrogen injector. The diesel fuel flow rate is reduced and the hydrogen flow rate is increased to maintain the engine power at the same level. The substitution of diesel fuel with hydrogen is evaluated with the energy substitute ratio, \( x_c \), defined with the relation:

\[
X_C = \frac{C_{hH_2}H_{hH_2}}{C_{hH_2}H_{hH_2} + C_{hmot}H_{hmot}}
\]

where \( C_{hH_2} \) - hydrogen consumption, \( C_{hmot} \) - consumption of diesel fuel, \( H_{hmot} \) – lower calorific value of diesel fuel, \( H_{hH_2} \) - lower calorific value of hydrogen.

In figure 2 are presented averaged (250 cycles) pressure diagrams for standard engine (\( x_c = 0 \)) and for diesel engine fuelled with diesel fuel and hydrogen in addition (\( x_c = 5.90\%, 10.87\%, 17.03 \) and 21.95\%) at 70\% engine load and 2000 min\(^{-1}\) speed. The maximum pressure and the pressure rise maximum rate start to rise for hydrogen addition due to the rise of fuel amount that burns during the premixed combustion phase, figure 2 and figure 3. The maximum pressure increases with 20\% and the pressure rise maximum rate increases with 25\% for 21.95\% substitute ratio of the diesel fuel comparative to standard diesel, being under limits values recommended.
Figure 2. Pressure diagrams versus substitute ratio at the engine regime of 70% engine load and 2000 min\(^{-1}\) speed.

Figure 3. The maximum pressure versus substitute ratio at the regime of 70% engine load and 2000 min\(^{-1}\) speed.

The diesel fuel combustion is intensified and due the presence of air-hydrogen mixture combustion. When the diesel engine is fuelled with hydrogen, the fuel quantity which burns during the premixed combustion phase increases and due to the higher heating value and higher combustion velocity of hydrogen will rise the rate of heat release, figure 5, and the amount of heat release, figure 7.

This influence can also be explained and by the increase of the amount of heat released during the combustion of the fuel pilot (after the diesel fuel pilot autoignition, the hydrogen existing in engine cylinder begin to burn), figure 5 and figure 6. The increase of the hydrogen addition will increase the amount of heat released during the combustion of the fuel pilot, figure 6.
Figure 4. The pressure rise maximum rate versus substitute ratio at the regime of 70% engine load and 2000 min\(^{-1}\) speed.

Figure 5. Heat release rate versus substitute ratio at 70% engine load and 2000 min\(^{-1}\) speed.

In the figure 8 is presented the brake specific energy consumption (BSEC) variation with the substitute ratio, \(x_c\), at the 70% engine load and 2000 min\(^{-1}\) speed. At the increase of the hydrogen addition, the brake specific energy consumption decreases with 8% for 21.95% substitute ratio of the diesel fuel comparative to standard diesel due to increase of the homogenous mixture amount and of the combustion improvement. The engine thermal efficiency increase from 31.9 to 34% for the same substitute ratio of the diesel fuel comparative to standard diesel.

Figure 7 presents the variation of NO\(_x\) emissions level. At the engine fuelled with hydrogen, NO\(_x\) emissions level decreases with 12% comparative to diesel engine at 70% load for a 10.87% substitute ratio of diesel fuel with hydrogen being achieved.
Figure 6. The amount of heat released from fuel pilot combustion versus substitute ratio at 70% engine load and 2000 min\(^{-1}\) speed.

Figure 7. Heat release characteristics versus substitute ratio at 70% engine load and 2000 min\(^{-1}\) speed.
Figure 8. Brake Specific Energy Consumption versus substitute ratio at 70% engine load and 2000 min\(^{-1}\) speed.

Figure 9. NO\(_x\) level versus substitute ratio at 70% engine load and 2000 min\(^{-1}\) speed.

The authors explain the NO\(_x\) emissions level decrease, at the engine operate with small hydrogen quantities in addition, as follows: firstly, although hydrogen burns rapidly, the gases temperature increases but NO\(_x\) emissions formation is avoided due to a shorter duration of the combustion and high temperatures are registered only for short time \(\sim 1.78\) ms; secondly, at the hydrogen combustion will increase the molar participation of water vapours in the combustion total products and they will absorb heat from all energy released from combustion and therefore the maximum combustion temperature decreases. At the hydrogen amount increase the temperature effect regarding the NO\(_x\) formation is high because the heat release is greater and the temperature rises for a high time duration.
The variation of HC and smoke emissions level is shown in figure 10 and figure 11. The smoke and HC emissions level is smaller comparative to diesel fuel with 20%, respectively 15% due to combustion improvement (hydrogen has a higher combustion velocity and the mixture fuel-air has a great homogeneity) and due to the lower content of carbon in mixture.

At the increase of the substitution ratio of the diesel fuel with hydrogen the CO$_2$ emission level decreases with 12% due to combustion improvement and due to the lower content of carbon in mixture, figure 12.
3. Conclusions
Experimental investigations carried out on a car diesel engine fuelled with hydrogen in the dual fuel mode, under constant load and speed engine operation (70% engine load and 2000 min⁻¹), allow drawing the following conclusions regarding the effects at the increase of the substitution ratio of the diesel fuel with hydrogen:

- the brake specific energy consumption slowly decreases,
- NOₓ emissions level decreases with 8% comparative to diesel engine for a 10.87% substitute ratio of diesel fuel with hydrogen,
- the HC and smoke emissions level decreases with 15% respectively with 25%.
- the CO₂ emissions level decreases with 6% for 17% substitute ratio of diesel fuel with hydrogen.

The hydrogen use at car diesel engine is a viable solution, especially for reducing pollution. The use of the hydrogen at the diesel engine by diesel-gas fuelling method does not required major modifications of engine design.

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