Experimental investigations of the hydrogen addition effects on diesel engine performance

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Abstract. In the global content regarding the impact on the environmental of the gases emissions resulted from the fossil fuels combustion, an interest aspect discussed on the 21st Session of the Conference of the Parties from the 2015 Paris Climate Conference and the gradual diminution of the worldwide oil reserves contribute to the necessity of searching of alternative energy from durable and renewable resources. At the use of hydrogen as addition in air to diesel engine, the level of CO, HC and smoke from the exhaust gases will decrease due to the improvement of the combustion process. At low and medium partial loads and low hydrogen energetic ratios used the NOX emission level can decrease comparative to classic diesel engine. The hydrogen use as fuel for diesel engine leads to the improving of the energetic and emissions performance of the engine due to combustion improvement and reduction of carbon content. The paper presents, in a comparative way, results of the experimental researches carried on a truck compression ignition engine fuelled with diesel fuel and with hydrogen diesel fuel and hydrogen as addition in air at different engine operation regimes. The results obtained during experimental investigations show better energetic and pollution performance of the engine fuelled with hydrogen as addition in air comparative to classic engine. The influences of hydrogen addition on engine operation are shown.

1. Introduction
A special attention is give to reduction of internal combustion engine pollutant emissions (hydrocarbons HC, carbon monoxide CO, nitrogen oxide NOₓ, particles PM and smoke) and of the greenhouse gas emissions (CO₂). Nowadays, a special legislation is promoted to limit the pollutants emissions by apply active and passive new methods for their reduction. The applied strategy’s for environmental pollution reduction makes the researches to focus on alternative fuel use [1], [2], [3] like hydrogen use. Hydrogen has a higher resistance to autoignition, fact that restrain its use as unique fuel at diesel engine, an ignition source being necessary [4], [5], [6], [7]. One recommended method for hydrogen use at diesel engines is the diesel gas method. Hydrogen is injected into the inlet manifold, the higher homogeneity air-hydrogen mixture being ignited by a flame initiated by autoignition of the diesel fuel injected inside the cylinder. Experimental research’s developed for compression ignition engine fuelled with hydrogen and diesel fuel by this method show same specific aspects comparative to diesel fuel fuelled engine. Thus, at the hydrogen diesel engine fuelling appear effects on combustion parameters in engine cylinder and on engine energetic performance: increase of maximum pressure and of the maximum pressure rise rate [8], [9], increase of the heat release maximum rate [10]; reduction of combustion duration [10]; power per litre increase [11]; increase of
indicated thermal efficiency at partial loads [12]; reduction of energetic consumption [10], [12]. At
engine running at the fuelling with hydrogen and diesel fuel, the CO, HC and smoke emissions has a
much lower level comparative to diesel engine fuelled with diesel fuel due to improvement of the
combustion, a lower carbon content in air-fuel mixture and a higher homogeneity of air-hydrogen
mixture [10], [11], [12]; slightly increase of the CO₂ emission level [12]. The level of the NOₓ
emission increases at the rise of the hydrogen addition, especially at large engine load because the in-
cylinder gases temperature is much higher comparative to the NOₓ formation temperature [12, 14]. N.
Saravanan [8], Younkins M. [12] and Tomita [13] show that the NOₓ emissions level decreases with
almost 14% at hydrogen fuelling in relative low additions (up till 15% energetically substitution of
diesel fuel) at small engine loads, due to a shorter duration in which the high temperature reached
inside the engine cylinder exists, the NOₓ emissions forming being avoided. At big hydrogen
additions, the level of NOₓ emissions increases, comparative to the emissions level of a standard
engine, because of the duration of maintaining high temperatures inside the cylinder [13, 14]. In the
paper are presented results of experimental research developed on a truck diesel engine, fuelled with
hydrogen additions, at 55% load and 1450 rev/min speed regime.

2. Methodology
The diesel engine D2156 MTN8 was mounted on a test bench equipped with an eddy-current
dynamometer and adequate instrumented with: data acquisition system, thermometers, thermocouples,
thermo resistances and manometers monitoring the engine functional parameters, air flow meter,
hydrogen flow meter, diesel fuel consumption device and gas analyzer. In the figure 1 the scheme of
the experimental test bed is presented.

The experimental research has been followed on the engine at the operating regimen of 55% load,
engine speed of 1450 rev/min and normal thermal regimen (80°C cooling agent temperature) for
different hydrogen flows.

The engine was fuelled firstly only with fuel diesel then with diesel fuel and hydrogen in addition
at different rate between 11.2 L/min and 40.4 L/min which correspond to some percents of substitute
energetic ratios of diesel.

The quantity of the diesel fuel substituted by hydrogen in air established by an energetic substitute
ratio value which takes into consideration the energetically value of the both fuels, xₑ [%]:

\[ xₑ = \frac{Ch_{H} \cdot Hi_{H}}{Ch_{DF} \cdot Hi_{DF} + Ch_{H} \cdot Hi_{H}} \times 100 \] (1)

where: \( Hi_{DF}, Hi_{H} \) represents the lower heating value of diesel fuel and hydrogen in [kJ/kg] and \( Ch_{DF}, \)
\( Ch_{H} \) are diesel fuel and hydrogen consumptions in [kg/h].

At only diesel fuelling the \( xₑ \) value is zero.

In order to explain the tendency of variation for the smoke emission from the exhaust gases at the
dual fuelling, the smoke quantity was calculated with the thermodynamic model, zero-dimensional,
two-zone, developed by authors. To establish a correlation with the measured values of smoke
emission, an author’s developed thermodynamic model uses the difference between speeds of soot
formation and oxidation. In order to evaluate the forming mass velocity of soot at the same engine
running regime, the Kuo correlation was used [15], [16], [17], [18]:

\[ m_f = C_f \cdot m_e \cdot p^{0.5} \cdot \exp \left( -\frac{6290}{T} \right) \] (2)

where: coefficient \( C_f = (2.5\ldots 5.0) \cdot 10^{-3} \), \( m_e \) mass of fuel in gaseous state, \( p, T \) in-cylinder pressure and
temperature.
The combustion of the soot particles is controlled by chemical reactions that take into consideration the phenomena’s of adsorption of oxygen at the particle surface and desorption of the reaction products from the particle surface. Velocity’s of adsorption and desorption of carbon monoxide at the particle surface depend in an exponential way by temperature [16], [17], [18]. The particle surface contains a very reactive zone, partial full of oxides in chemical equilibrium and a less reactive zone. Practically, the global mass speed on surface unit for soot oxidation is established by summarizing of desorption velocities of the considered reactive zones, [16], [17], [18].

\[
v = M_e \cdot \left[ x_A \cdot \frac{K_{a_o} \cdot P_O}{1 + K_A \cdot P_O} + K_{b_o} \cdot P_O \cdot (1 - x_{a_o}) \right]
\]

where coefficient \( M_e = 12 \) is the carbon molecular mass.

The \( x_A \) is a surface fraction related with a very reactive zone and the \( 1 - x_A \) fraction represent the less reactive zone. The surface fraction filled by oxides \( x_{a_o} \) is defined by the equilibrium between
oxygen adsorption velocity from gaseous state for oxides forming and carbon monoxide desorption velocity from the droplet surface. With $x_{Ao}$ is determinates the velocity of carbon monoxide release after the oxidation into the very reactive zone takes place. Into the less reactive zone, the oxygen participate to a slow oxidation reaction that leads to the generation of a new active zone, followed by desorption of carbon monoxide with the velocity $K_{Ba} p_0 (1-x_A)$. Also, during a phenomenon of chemical arrangement by thermal activation, the very reactive zone creates a new low reactive zone, with velocity of $K_T x_A [17], [18]$.

Finally, the expressions

\[ K_{Ad} = 20 \cdot \exp\left(-\frac{15098}{T}\right) \]  
(4)

\[ K_{Ba} = 4.46 \cdot 10^{-3} \cdot \exp\left(-\frac{7650}{T}\right) \]  
(5)

\[ K_T = 1.51 \cdot 10^{5} \cdot \exp\left(-\frac{48817}{T}\right) \]  
(6)

\[ K_Z = 21.3 \cdot \exp\left(-\frac{2063}{T}\right) \]  
(7)

\[ K_{Ad} = \frac{K_{Ba}}{K_Z} \]  
(8)

are the semi-empirical relations of the velocity’s [17], [18] with units $K_{Ad}$, $K_{Ba}$ [g∙cm$^{-2}$∙s$^{-1}$∙bar$^{-1}$], $K_T$ [g∙cm$^{-2}$∙s$^{-1}$], $K_Z$ [bar$^{-1}$].

At relative low temperatures and partial pressures of oxygen, the entire surface is defined as a very reactive zone, $x_A=1$, the term $K_T$ being negligible. The fraction $x_A$ decreases once with the temperature increasing and becomes negligible comparative to coefficient $K_{Ba}$ of desorption velocity at high temperatures [17], [18]. With this relation the velocity of soot formation and oxidation are determined and calculated by integration for soot formation and oxidation laws determination.

From the soot balance, defined by the difference between formation and oxidation of soot quantities for diesel fuelling and dual fuelling, is establish the smoke relative final quantity (SFQ [%]) in the exhaust gases for each substitute ratio. For the soot balance the following relation is use:

\[ \left(\frac{m_{M} - m_{H}}{m_{M}}\right)_{ex} = 100 \cdot \left(\frac{m_{M} - m_{H}}{m_{M}}\right)_{f} - \left(\frac{m_{M} - m_{H}}{m_{M}}\right)_{o} \]  
(4)

where: $m_M$, $m_H$ represent the relative quantises of diesel fuel and hydrogen, $f$, $o$, $ex$ indices with signification of formation of soot, oxidation of soot and exhaust quantity of soot from the exhaust gases.

3. Results

From in-cylinder pressure diagrams the heat release diagrams were calculated for the regime of 1450 rev/min and 55% engine load. The rate of heat release characteristics for all substitute ratios of diesel fuel by hydrogen are presented in the figure 2. At hydrogen use, the peak values of heat release rate remains in the same domain with values registered for diesel fuel, for all substitute ratios, but the moment of peak values are reached sooner per cycle, closer to TDC. The heat release rise rate increases at the hydrogen use comparative to diesel fuelling due to a better combustion, figure 2, fact that is in correlation with a sooner achievement per cycle of moment when maximum values of heat release rate occurs and influence the aspect of heat release laws, figure 3.
Figure 4 shows the continuous decreasing in variation of brake specific energetic consumption (BSEC) with substitute ratios. The BSEC decreases at the increase of hydrogen addition in inlet air.

**Figure 2.** Heat release rate for different $x_c$ at 55% load and 1450 rev/min regime.

**Figure 3.** Heat release law for different $x_c$ at 55% load and 1450 rev/min regime.

The lowest BSEC of 9550 kJ/kWh is achieved for $x_c=3...3.9$, corresponding to a hydrogen rate of 31.2,...,40.2 L/min, versus to the value registered only for diesel fuelling of 10550 kJ/kWh, due to better homogeneous fuel-air mixture and the combustion improvement. The percentage of BSEC reduction is around 10% versus classic fuelling solution. Due to combustion improvement and lower carbon content in the air-fuel mixture at hydrogen rate increase the smoke emission level, evaluated by $K$ smoke number, decreases comparative to classic fuelling solution, figure 5. During combustion
hydrogen forms a homogeneous mixture versus heterogeneous mixture which is specific to diesel engine, fact that contribute to the reduction of the smoke emission. Forward increase of hydrogen inlet quantity, which affect the combustion temperature, leads to an slightly increase tendency for smoke number without exceeding the standard engine values. The smoke variation tendency registered during experimental investigation, for a limited domain of substitute ratio variation, can be explained thru the combined effect of in-cylinder pressure and temperature. Combustion improvement and the lower carbon content of the air-fuel mixture lead to the decrease of the level for CO₂ emission, figure 6, and CO emission, figure 7, when the hydrogen cycle quantity increase. The CO emission decreases also due to higher burning velocity of hydrogen which accelerate the diesel fuel combustion at engine regimes of small loads.

![Figure 4](image-url)  
**Figure 4.** BSEC versus xₖ at 55% load and 1450 rev/min regime.

![Figure 5](image-url)  
**Figure 5.** Smoke number versus xₖ at 55% load and 1450 rev/min regime.
Combustion improvement and the lower carbon content of the air-fuel mixture lead to the decrease of the level for CO₂ emission, figure 6, and CO emission, figure 7, when the hydrogen cycle quantity increase. The CO emission decreases also due to higher burning velocity of hydrogen which accelerate the diesel fuel combustion at engine regimes of small loads.

Figure 8 shows the variation of NOₓ emissions level with diesel fuel substitute ratios with hydrogen. Comparative to classic engine, in hydrogen-diesel dual fuelling operation mode NOₓ emissions level decreases with 5.5% at maximum xc.
At the engine small loads and hydrogen use the diesel-fuel cycle dose is reduced and the high effect of combustion temperature on the NOX formation is reduced. At the hydrogen adding, at the same engine load, the cycle dose of diesel fuel and the combustion duration decreases, at same load regime, the heat release rate slightly decreases lead to global temperature and NOX decreasing. In consecutive cycles, the combustion duration with higher heat release rate comparative to diesel fuelling is shorter.

The maximum values of in-cylinder global temperature, calculated with the thermodynamic model, decreases with ~14% comparative to reference engine, from 1600 K at xc=0 down till 1375 K….1503 K at xc=1.1,…, 3.9, below the values of NOX thermal formation, fact that can explain the NOX emission reduction. In case of fuelling with small hydrogen quantities in addition in inlet air, the explication for NOX emissions level decrease is the fact that hydrogen burns fast, leading to the avoiding of NOX formation due to a shorter duration of the combustion and high temperatures (registered in some consecutive cycles) are registered only for short time ~1.8 ms – 2 ms, (“the combustion is so rapid that the high temperatures exist only for approx. 2ms.” after Georgios Pechlivanoglou, [19]). Whatson [20] and Thalibi et al. [21] explains NOX decrease at the hydrogen adding in air through the increase of the mole fraction of water vapours in the combustion products produced at the hydrogen combustion which absorb energy released from combustion and thus the peak combustion temperatures decrease [21], which is in correlation with the anterior mentioned reduction for the maximum values of gases temperature.

Due to the fact hydrogen don’t contain carbon and has higher burning velocity versus diesel fuel and due to the general combustion improvement, the HC emissions level decreases at hydrogen use, figure 9. The HC emissions level decreases comparative to diesel fuelling not only due to combustion improvement but also due to lower carbon content in the final fuel-air mixture. The higher burning velocity of hydrogen accelerates the diesel fuel combustion at small engine loads, the HC emission being reduced.

The soot forming law is presented in the figure 10 and the soot oxidation law in the figure 11. For only diesel fuelling the soot formation is maximum (100%) and the oxidation also registered the maximum value, as figure 11 shows. At xc=1.1 the soot formation represents ~60%, initially being obtained with 34% less soot inside the cylinder, but the oxidation of formed soot being with 49% less efficient comparative to diesel fuelling.
For $x_c = 2.2$ soot formation represents 70% and the soot quantity formed inside the engine cylinder being with 30% lower comparative to classic engine. The soot oxidation is assured in the same terms of the previous lower value of $x_c$.

![Figure 9](image-url)  
*Figure 9.* HC versus $x_c$ at 55% load and 1450 rev/min regime.

Actually, for substitute ratios up till $x_c = 2.2$, the soot oxidation is developed in a much efficient way comparative to other substitute ratios. For $x_c = 3$ the most lower value of soot formation is obtained, comparative to diesel fuel, and the lowest value of soot oxidation of 20%, with 80% less versus diesel fuel but in terms of an initial smoke emission with 53% lower comparative to diesel fuel.

![Figure 10](image-url)  
*Figure 10.* Soot forming law for different $x_c$. 

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Figure 11. Soot oxidation law for different $x_c$.

At substitute ratio of $x_c=3.9$, the quantity of soot is with 43% lower comparative to diesel fuel, the oxidation of the soot being reduced with 67% versus diesel fuel. The increase of the substitute ratio from $x_c=3$ to $x_c=3.9$ leads to the increase with 13% of soot oxidation intensity, in terms of a 67% lower soot formation comparative to diesel fuel.

Figure 12. Smoke relative emission for different $x_c$.

The height oxidation rate is registered for diesel fuelling, figure 11. The soot oxidation registered for dual fuelling is less intensive comparative to diesel fuel, but the soot quantities formed inside the cylinder are with 30%...34% lower for $x_c=1.1...2.2$ and with 43%...53 % for $x_c=3... 3.9$. Higher hydrogen rates influence more significant the oxidation process, also assuring the formation of a lower quantities of soot, whereas the smaller hydrogen rate has a higher influence on soot formation process.
Figure 12 shows the variation of the smoke relative emission, theoretically determinate and compared with the experimental values, stated in relative values of smoke number reported to the condition $x_c=0$. Thru speeds and laws of formation and oxidation of the soot can be explained according to the variation of the pressure and temperature regimes the reduction of the smoke emission at dual fuelling, followed by a slightly increase tendency after a specific $x_c$ value, without exceeding the values registered for $x_c=2.2$ or for diesel fuelling.

4. Conclusions

The experimental investigations carried on a diesel engine dual fuelled with hydrogen by intake manifold injection at the regime of 55% load, 1450 rev/min and different energetic substitute ratios in the area of 1.1%...3.9% leads to the formulation of the following main conclusions: due to higher hydrogen burning velocity the heat release rate increases with the rise of the hydrogen cycle dose and the registered values are reached sooner per cycle comparative to diesel fuelling; hydrogen use in dual fuel operation leads to a decrease of almost 10% in terms of brake specific energetic consumption (BSEC) comparative to standard diesel engine; at the hydrogen-diesel oil dual fuelling operation mode NOx emissions level decreases with 5.5% comparative to diesel engine for a 3.9% percent of substitute ratio of diesel fuel by hydrogen; comparative to classic engine, the HC and smoke emissions level decreases at the hydrogen addition increase; the tendency of variation experimentally registered at the reduction of the smoke emission from the exhaust gases is explained by the combined effect of pressure and temperature of in-cylinder gases; soot quantity formed inside the engine cylinder decreases at the increase of hydrogen quantity, for all substitute ratios, the reduction being around 53% at the maximum hydrogen rate; at dual fuelling, higher hydrogen quantity accelerate the soot oxidation process comparative to lower hydrogen quantities; the CO and CO$_2$ emissions register continuous reduction tendency for all domain of substitute ratios, with values under the reference regime, $x_c=0$; hydrogen in addition at diesel fuel is a promising alternative fuel for diesel engines; the application of diesel-gas method for use of hydrogen in addition at diesel fuel don’t require major modifications of the engine design.

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