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Review article

Aspects of an experimental study of hydrogen use at automotive diesel engine[☆]

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ABSTRACT

Hydrogen may represents a good alternative fuel that can be used to fuel internal combustion engines in order to ameliorate energetic and emissions performance. The paper presents some experimental aspects registered at hydrogen use to fuel a diesel engine, different substitute ratios being use in the area of 18–34%, at 40% engine load and speed of 2000 rev/min. The engine is equipped with an open ECU and the control of the cyclic dosses of diesel fuel and hydrogen are adjusted in order to maintain the engine power performance. The in-cylinder pressure diagrams show the increase of the maximum pressure with 17%, from 78.5 bar to 91.8 bar for the maximum substitute ratio. Also, values of maximum pressure rise rate start to increase for hydrogen addition, in correlation with the increase of fuel amount burned into the premixed stage, without exceed the normal values with assure the normal and reliable engine operation. Higher Lower Heating Value and combustion speed of hydrogen assure the increase in thermal efficiency, the brake specific energy consumption decreases with 5.4%–7.8% at substitute ratios of 20–27%. The CO_2 emission level decreases with 20% for maximum hydrogen cyclic dose. In terms of pollutant emission level, at hydrogen use the emission level of the NO_x decreases with 50% and the smoke number decreases with 73.8% comparative to classic fuelling at the maximum hydrogen cyclic dose.

1. Introduction

In the near future the production and use of hydrogen in different areas of science will be more under the spot line, the green method of hydrogen production being more and more sought after, showing more interest. Looking to alternative solutions to decrease the dependence on classic fuels, the production of hydrogen from solar energy can represent a solution [1]. The improvement of the hydrogen production from nicked catalysts shows a good perspective in the field of hydrogen production and applications [2]. The area of hydrogen use in different applications is very wide from medicine [3] to mechanical engineering. Hydrogen can be use to fuel a stationary engine which support the electric network of a hospital or to fuel the ambulance automotive engine. The use of hydrogen to ameliorate the energetically and pollutant emissions level at internal combustion engines can be a viable solution [4]. For the future

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years of 2030–2050 the use of sustainable energy strategies and application of the environmental protection measurements may represent an important demand for the diesel engine [5,6]. The use of alternative fuels to fuel diesel engine in the future may lead to advantages like reduction of the CO_2 emission and of the pollution gases, engine efficiency improvement, reducing dependence on classic fuels etc. Fumigation with different fuels can assure the improve the diesel engine performance in terms of combustion and pollutant emissions, like CO, NO, smoke and GHG as CO_2 [5]. Of all the alternative fuels, hydrogen seems to have the most promising prospects for use as an alternative fuel to the diesel engine and hydrogen fumigation also can be use. Fumigation at diesel engine can be done with various alternative fuels, like LPG, CNG, hydrogen. Hydrogen may be a good alternative fuel which can be used to fuel automotive diesel engines in order to improve energetic and emissions performance. The use of hydrogen in dual fuelled engines will assure the possibility of keeping them in use in the future years, the conversion to the use of hydrogen can be applied to the new engines and to the old generation engines which are already in operation.

Researchers in the field of internal combustion engines have studied the effects of hydrogen use on engine performance, the influences on the level of polluting emissions and greenhouse gases, respectively on the combustion process being the most important. In the specialty literature there is not much information about the use of hydrogen at the diesel engine, but currently there is starting to be a more significant interest in its use as an additional fuel to the diesel engine, in order to replace the classic fuel and to improve the diesel engine performance.

Hydrogen use may improve the combustion process due to its good burning qualities, Table 1, as wide flammability limits, higher lower heating value, flame speed comparative to classic fuel, properties which defines hydrogen as a good viable alternative fuel for diesel engine [7].

Different researchers use hydrogen as alternative fuel to fuel different diesel engines and their research results show the influence of hydrogen on combustion process and engine performance. As example, Estrada et al. [8] shows that hydrogen use assure the reduction of the brake specific fuel consumption, increase of the thermal efficiency, decrease of pollutant emissions level for CO, HC, decrease of the greenhouse gas CO_2, but increase of the NO_x emission level [8].

Kavtaradze et al. [9] shows the main advantages of hydrogen use like the increase of the fuel efficiency, the reduction of the pollutant emissions levels, as soot or nitrogen oxides, the reduction of the greenhouse gas CO_2, but the combustion of hydrogen may leads to the increase of maximum pressure and of maximum pressure rise rate. Koten et al. [10] uses hydrogen to fuel a diesel engine and he observes that addition of hydrogen in the engine inlet leads to the increase of brake specific fuel consumption, decrease of soot emission level for all hydrogen flows, but NO_x emission level increase especially at high engine loads. In his experiment, Zhang et al. [11] observes that hydrogen addition (in percent's of 15% … 35%) assure the increase of the engine thermal efficiency, but NO_x emission level increase till 83% depending on air-fuel ratio value. The increase of hydrogen percent leads to the increase of maximum pressure with almost 30% and of the maximum value of the pressure rise rate with 66% during combustion. Demirci et al. [12] shows that small hydrogen quantities injected into engine inlet leads to the decrease of brake specific fuel and energy consumption, increase of engine thermal efficiency. Higher NO_x emission level is observed at the increase of hydrogen dose at the regime of full load. At other operating loads, the NO_x emission level was decreased with the increase of hydrogen quantity till 2.5% [12]. Smoke emission level was decreased till 27.5% for maximum hydrogen quantity [12]. For full load regime, the CO_2 emission level decrease with 0.81%, but for other regimes the decrease of CO_2 emission level is more significant, till 12.6%, depending the hydrogen dose. Santoso et al. [13] uses hydrogen to fuel a diesel engine at regime of 2000 rev/min and different loads and he shows that the increase of the hydrogen flow leads to the increase of in-cylinder pressure at higher loads regimes, but decreases at low load, similar tendency being recorded for fuel efficiency, for many hydrogen flows the efficiency remains in the area of classic fuelling operation [13]. Only for maximum hydrogen flow the engine efficiency decrease with 6% and 9% at medium and high loads [13]. The maximum pressure and the heat release rate decrease when the hydrogen addition percent increase, at low loads, but for higher engine loads the heat release rate starts to increase with 25% for the peak registered, the maximum pressure rise with ~6.4% values [13]. Sughayyer et al. [14] shows that hydrogen use leads to the increase of engine power and to the decrease of pollutant emissions level, especially for CO. Loganathan et al. [15] shows that the use of hydrogen assure the increase of combustion pressure, but its maximum values can be reduced by Exhaust Gas Recirculation (EGR) use, even the EGR increase leads to the increase of cyclic variations of maximum pressure values. Ghazal [16] develops a simulation of hydrogen use at a diesel engine resulting a decrease of the pollutant emission levels, decrease the pressure rise rate. Lata

Table 1
Properties of hydrogen and diesel fuel [7].

Properties	Hydrogen	Diesel fuel
Formula	H_2	$C_{16}H_{34}$
Density at 16°C and 1.01 bar [kg/m^3]	0.0838	833–881
Auto-ignition temperature [K]	858	530
Flammability limits [vol. % in air]	4–75	0.7–5
Min. ignition energy [mJ]	0.02	–
Stoichiometric air mass quantity [kg air]	34.32	14.5
Net heating valve [MJ/kg]	119.617	41.855
Limits of flammability (λs-λi)	0.13–10.8	0.34–1.68
Flame speed [cm/s]	265–325	30
Diffusivity in air [cm^2/s]	0.63	–
Quenching gap in NTP air [cm]	0.064	–
Cetane number	–	44–55
Octane number	130	30

et al. [17] uses hydrogen and LPG to fuel a turbocharged diesel engine, following the dual fuelling influence on engine performance and emissions level. For only hydrogen use, the brake thermal efficiency increase with 17%, for 30% hydrogen and 70% diesel fuel. The levels of the NO_x and smoke emission decrease at hydrogen use comparative to classic fuelling. Similar results were obtained for LPG use or for LPG-hydrogen mixture use, in the same experimental conditions [17]. Deb et al. [18] uses different hydrogen energetically proportions, from 0% to 42% to fuel the admission of a diesel engine, at 1500 rev/min and low load regime, observing that the brake thermal efficiency is improved and the brake specific energy consumption BSEC decreases for hydrogen use. The CO_2 and smoke emissions levels start to decrease with the increase of hydrogen content, but the NO_x emission level increases for higher hydrogen quantities [18]. Karagoz et al. [19] remarks the increase of brake specific fuel consumption at hydrogen use at a diesel engine, similar to the reduction of the thermal efficiency, at all running speeds. A 25% appears in CO_2 emission decrease, the level of the smoke emission decrease with 51% for 25% hydrogen addition, but the NO_x emission level is increased with a maximum of 39% by 25% hydrogen addition [19]. For 50% hydrogen addition, the smoke emission level decreases with 58%, the CO_2 decreases with 38%, but the increase of NO_x is above 200% [19]. The maximum pressure increases with 11% for 25% hydrogen content and with 34% for 50% hydrogen content [19]. Morais et al. [20] shows the reduction with 12% of the CO_2 emission level at 20% hydrogen use to replace the diesel fuel, in terms of a similar engine efficiency registered at classic fuelling for a diesel engine. Kose et al. [21] uses different hydrogen quantities, 2.5% … 7.5%, to fuel a turbo-supercharged diesel engine, showing the increase of thermal efficiency and of the NOx emission level once with the increase of hydrogen content. The specific fuel consumption is lower for hydrogen use in small quantities like 2.5% and 5%, but slightly increase for 7.5% hydrogen percent. The CO_2 emission level is generally decreased by hydrogen use, the decrease being more significant with the rise of hydrogen content [21]. Adnan et al. [22] shows that hydrogen addition assure the increase of maximum pressure during combustion, from 5 bar to over 20 bar depending on hydrogen cyclic content. For the same hydrogen percent's, the levels of the NO_x and CO_2 emission were increased with 50–200 ppm and 1%–4%, respectively [22].

The paper presents some experimental aspects registered at hydrogen use to fuel a diesel engine, different substitute ratios being use. The influence of hydrogen cyclic dose on pressure diagrams, brake specific energy consumption, CO_2, NO_x and smoke emissions level are presented.

2. Experimental methodology

The experimental test bed is presented in Fig. 1. During the experimental investigation the energetically percent of substitution of diesel fuel with hydrogen is evaluated with a substitute ratio, SR, calculated based on the fuels mass consumptions and Lower Heating Values of the fuels. First of all the diesel engine is fuelled with diesel fuel and all the experimental data acquisitioned at this case represent the reference, defined by a substitute ratio equal to zero, SR = 0. Secondly, for dual fuelling operation, the diesel engine is fuelled with hydrogen and diesel fuel, at different substitute ratios which defines the percent of energetically substitution of diesel fuel by hydrogen, the SR used being in the range of 18 … 34, for the operating regime of 40% engine load and 2000 rev/min speed. Hydrogen is injected into the inlet manifold and the cyclic dose is controlled via an open Electronic Control Unit (ECU) which commands the hydrogen injector mounted in the final section of the intake manifold. The open ECU is controlled with a Dastek software available on a computer. At dual fuelling mode operation first, the cyclic dose of the diesel fuel is reduced by reduction of the diesel injectors opening duration, the effect of power decrease being present. Secondly, via open ECU the opening of the hydrogen injector is commanded, the opening duration of the hydrogen injector being established from the considerations of restoring the engine power to the value assigned to the operation when only diesel fuel is used.

The notations in Fig. 1 have the following meaning: *E*-diesel engine K9K, *D*-electric dyno, *AF*-air flow meter, *HI*-hydrogen injector,

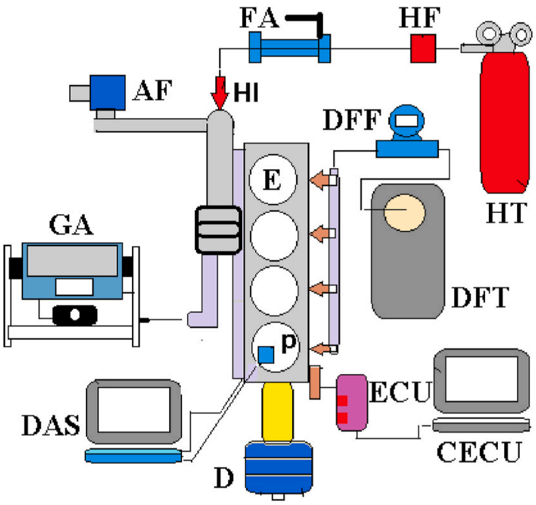

Fig. 1. Experimental test bed schema of the diesel engine fuelled with diesel fuel and hydrogen.

FA-flame arrestor, *HF*-Alicat Scientific hydrogen flow meter, *HT*-hydrogen tank (gas tank type), *DFT*-diesel fuel tank, *DFF*-diesel fuel flow meter, *ECU*-electronic control unit, *CECU*-computer of ECU, *p*-AVL in-cylinder pressure transducer, *DAS*-AVL data acquisition system, *GA*-AVL gas analyser.

The precision of experimental data recorder with the specific apparatus are presented in Table 2 [23–27].

During the experimental investigation the tune of different engine parameters is set up in order to decrease the level of the pollutant emissions levels. The novelty of the paper is assured by the following aspects: efficiently use of hydrogen as alternative fuel to fuel the diesel engine, an optimum correlation established between *engine load-hydrogen cycle quantity-injection timing-diesel fuel cycle quantity-supercharging pressure-exhaust gas temperature* being established in order to control the combustion process and to obtain the best ecological and energetically performance of the engine at hydrogen and diesel fuel fuelling.

3. Results of the experimental investigation and discussion

The experimental investigation was carried on in a mode which assure the reduction to the minimum of the errors by recording a three sets of measurement for each experimental parameter. To evaluate the error analysis for the obtained results the variation ratio was determined:

$$VR = \frac{\sqrt{\frac{1}{a} \bullet \sum_{i=1}^{a} \left(z_i - \frac{\sum_{i=1}^{a} z_i}{a} \right)^2}}{\frac{\sum\limits_{i=1}^{a} z_i}{a}}$$

The values obtained for the variation ratio were bellow 1% and the values was below the convergence limit of each measurement series. For the coefficient of variation with values in the field of 0–10% the dispersion of the data is low and the measurements sample is homogeneous.

In Fig. 2 the in-cylinder pressure diagrams, smoothed and averaged, for different substitute ratios SR are presented. The pressure diagrams were obtained from averaging of 250 consecutive combustion cycles. Comparative to classic fuelling at hydrogen use, the maximum pressure increase doesn't exceed 20% limit at the maximum substitute ratio. Also, values of maximum pressure rise rate start to rise for hydrogen addition, in correlation with the increase of fuel amount burned into the premixed stage, without exceed the normal values domain with assure the normal and reliable engine operation.

The increase of the lower heating value of the in-cylinder mixture at hydrogen use, comparative with classic fuelling and the higher combustion speed of air-hydrogen mixture versus air-diesel fuel mixture at hydrogen use leads the increase of the heat release rate, increase of the combustion speed and reduction of the total combustion duration, aspects that assure the increase of the combustion pressure. The higher maximum pressure rise rate registered at air-hydrogen mixture combustion versus classic combustion leads to the increase of the peak value of the in-cylinder pressure. Also, the wider flammability limits of hydrogen $\lambda_s = 0.13$ ….$\lambda_i = 10.08$, comparative to diesel fuel, $\lambda_s = 0.37$ ….$\lambda_i = 1.68$, leads to the reduction of the initial phase of combustion which also leads to the rise of the maximum pressure. Thus, at the use of the 18% substitute ratio (SR = 18) the peak value of the pressure is with 4.56% higher comparative to classic fuelling. For 27% substitute ratio (SR = 27%) the value of the maximum pressure is with 7.84% above the value allocated to the classic fuelling, SR = 0. For the maximum substitute ratio, SR = 34%, the maximum value of pressure reached during air-diesel fuel-hydrogen mixture combustion is with 18.95% higher comparative to diesel fuel fuelling, SR = 0. Similar results which shows the increase of the maximum pressure and of the maximum pressure rise rate at the increase of hydrogen cyclic dose were registered also by other researchers, [9,11–22].

Hydrogen has a raised Lower Heating Value (LHV), 119617 kJ/kg, comparative to classic fuel, 41855 kJ/kg for diesel fuel, which influence the lower heating value of the in-cylinder mixture [7]. At hydrogen use, at SR = 18% the lower heating value of the in-cylinder mixture is with 33.44% higher comparative to classic fuelling. For SR = 27% the LHV of the air-fuel mixture is with 50.16% above the LHV of the classic fuel and at SR = 34% the LHV of the in-cylinder mixture increases with 63.17% comparative to classic fuelling, SR = 0. The higher combustion speed of air-hydrogen homogeneous mixture versus combustion speed of air-diesel fuel mixture, 30 cm/s versus 265 cm/s, assure the acceleration of the combustion process and in association with the increase of the LHV of the in-cylinder mixture at H_2 use, an increase in thermal efficiency, once with the rise of substitute ratios, may appear. The combustion efficiency is evaluated based on the brake specific energy consumption that is calculated taking into consideration the brake specific fuel consumption and the Lower Heating Value of the diesel fuel and hydrogen, according to their share established by the substitute

Table 2
Uncertainties of the measured parameters according to the used equipment's [23–27].

Parameter	Uncertainties	Measure Unit
Pressure (transducer AVL GU12)	0.05%	bar
Angle encoder AVL 365CC	±0.1 CAD	Crank Angle Degree
diesel fuel consumption Krohne Optimass	±0.1%	kg/h
hydrogen consumption Alicat Scientific	±0.05	kg/h
CO_2	0.1%	% vol.
NO_x	1 ppm	ppm vol.
smoke (K smoke number)	0.01 m^{-1}	m^{-1}

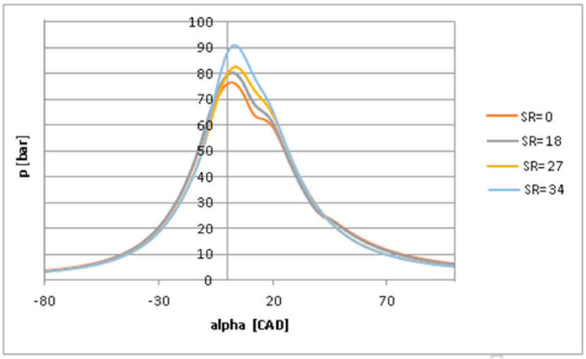

Fig. 2. Pressure diagrams at different substitute ratios.

ratio, SR. At hydrogen use, the brake specific energy consumption, Fig. 3, starts to decrease with 7.8% at SR = 20 … 27%. Also at the maximum substitute ratio the BSEC is with 5.4% lower comparative to diesel fuelling, Fig. 3.

Similar trends of variation that show the increase of thermal efficiency and decrease of the brake specific energy consumption at the increase of hydrogen quantity were registered also by other researchers, [8,11–21].

The acceleration of the combustion process at hydrogen use and reduction of the total amount of carbon inside engine cylinder at hydrogen use the level of the carbon dioxide is reduced at hydrogen–diesel fuel fuelling comparative to classic fuelling. The CO_2 emission level, Fig. 4, continuously decrease at the increase of hydrogen cyclic dose. For the substitute ratio SR = 27 the lowest CO_2 emission level is achieved, with 20% lower comparative to classic fuelling. For maximum hydrogen cyclic dose the CO_2 emission level is with 11.6% lower comparative to reference. The reduction of the available oxygen in a more significant way at the maximum SR, the level of the CO_2 is increased at SR = 34% comparative to the SR = 27%, but without exceeding the value allocated to classic fuelling. The reduction of the CO_2 emission level can be assured without affect the engine efficiency, the BSEC value being limited at 12385 kJ/kWh. The CO_2 emission level is related with the reduction of the mass composition of carbon in the final mixture at 0,6958 (69.58 %C) for SR = 18, at 0,6194 (61.94 %C) for SR = 27 and at 0,5601 (56.01 %C) for SR = 34, Fig. 5, and combustion improvement at hydrogen use.

The lower amount of carbon in the composition of cylinder mixture, compared to diesel fuel (considered as cetane), actually implies the reduction of the initial amount of carbon available in the cylinder at the beginning of the combustion process, Fig. 5, which subsequently leads to lower amounts found in the exhaust gases, aspect which also influence the CO_2 emission level. Similar results which shows the decrease of the CO_2 emission level at the increase of hydrogen cyclic dose were registered also by other researchers [.

In terms of pollutant emissions, the level of NO_x and smoke emissions are the most important at diesel engine. Comparative to classic fuelling, at hydrogen use the reduction of NO_x and smoke emissions level appears for all values of the substitute ratio, SR = 18% …. 34%. At hydrogen use, the level of the NO_x emission decreases with maximum 50% at SR = 34, for other substitute ratios the decrease being around 39% for SR = 18 and 47.5% at SR = 27 comparative to classic fuelling, SR = 0, Fig. 6. The reduction of the emission level can be explained by the reduction of the oxygen quantity available inside cylinder once with the rise of the hydrogen quantity injected into the inlet system, the coefficient of excess air λ being decreased with 11.2% at SR = 18, with 12.7% at SR = 27 and with 17.3% for SR = 34, Fig. 7.

At hydrogen use, the reduction of the amount of diesel fuel which burns during the premixed phase of combustion leads to the reduction of the nitrous oxides emission level, Fig. 6.

Similar trends of variation that show the decrease of the NO_x emission level at the increase of hydrogen quantity were registered also by other researchers [4,8,12–17,20,21].

The smoke emission level is evaluated based on the K smoke number, Fig. 8. At hydrogen use, the emission level of the smoke

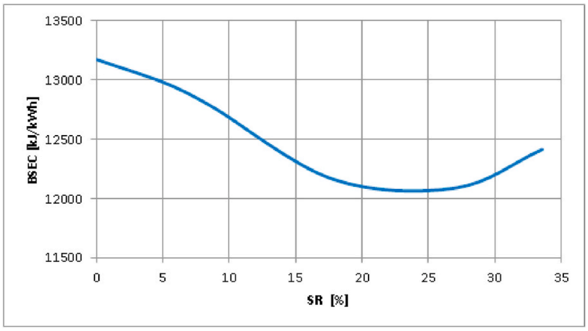

Fig. 3. The brake specific energy consumption BSEC versus substitute ratio.

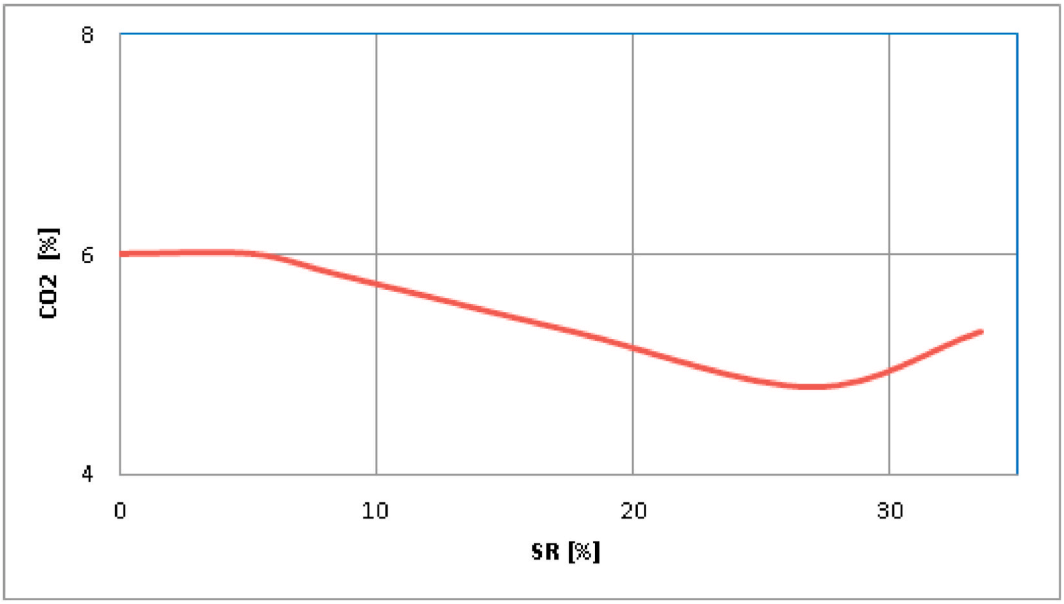

Fig. 4. The CO_2 emission level versus substitute ratio.

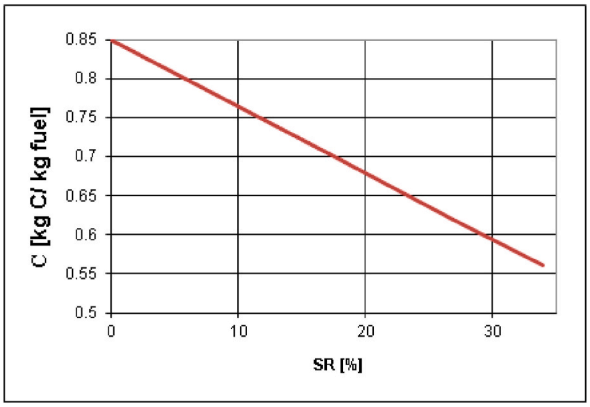

Fig. 5. The carbon content in the final mixture versus substitute ratio.

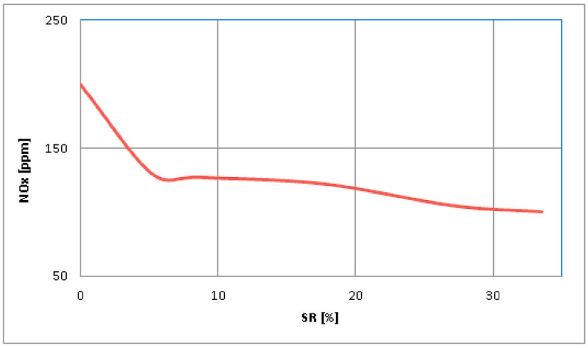

Fig. 6. The NO_x emission level versus substitute ratio.

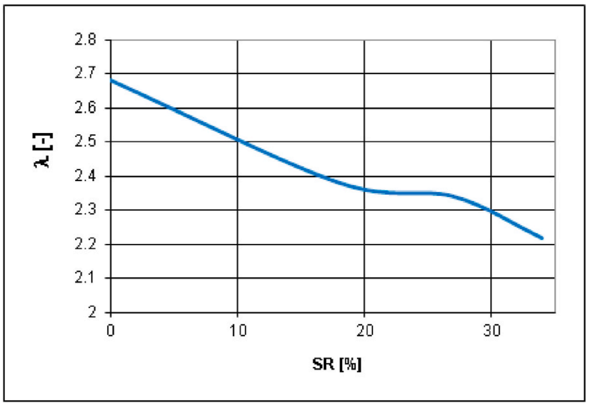

Fig. 7. The global coefficient of excess air versus substitute ratio.

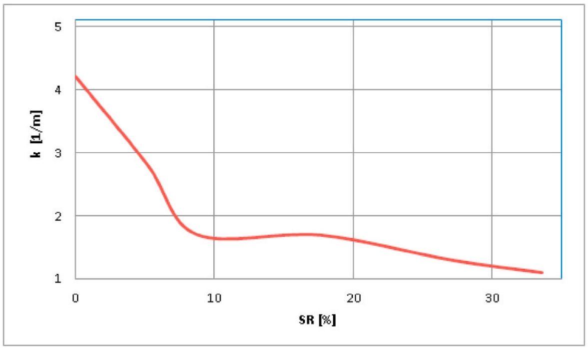

Fig. 8. Smoke emission level versus substitute ratio.

continuously decrease, for all substitute ratios, comparative to classic fuelling. At hydrogen and diesel fuel use, the smoke number decrease with 33.3% for SR = 9, with 59.7% at SR = 18, with 69% at SR = 27 and with 73.8% for maximum SR = 34, comparative to classic fuelling, Fig. 8.

The reduction of the smoke emission level at hydrogen use is correlated with the reduction of the carbon content in the in-cylinder final mixture comparative to classic fuelling, Fig. 5. The increase of the LHV of the air-fuel mixture at hydrogen use, the increase being more significant at the increase of the hydrogen cyclic dose, leads to the increase of the soot oxidation temperature that accelerate the in-cylinder process of soot oxidation. A more rapid soot oxidation in terms of a lower soot formatted quantity, influenced by lower carbon content, Fig. 5, leads to the reduction of the smoke emission level in the exhaust gases, Fig. 8.

Similar trends of variation that presents the decrease of the smoke emission level at the increase of hydrogen inlet quantity were registered also by other researchers, [4,9–19].

4. Conclusions

The use of hydrogen as addition alternative fuel to fuel an automotive diesel engine in dual mode leads to the formulation of the following main conclusion:

- the maximum pressure is increased with 17% at the maximum substitute ratio. The values of maximum pressure rise rate start to increase for hydrogen addition, in correlation with the increase of fuel amount burned into the premixed stage, without exceed the normal values domain with assure the normal and reliable engine operation;
- the brake specific energy consumption BSEC starts to decrease with 7.8% at SR = 20 … 27% and with 5.4% at the maximum substitute ratio due to hydrogen raised Lower Heating Value and its higher combustion speed;
- the CO_2 emission level decreases with maximum 20% for substitute ratio SR = 27, also a reduction with 11.6% at maximum hydrogen cyclic dose being assured versus classic fuelling;
- the level of the NO_x emission decreases with maximum 50% at SR = 34, for other substitute ratios the decrease being around 36.5% for SR = 9, 39% for SR = 18 and 47.5% at SR = 27 comparative to classic fuelling also due to reduction of the in-cylinder available oxygen quantity;

- the smoke emission level continuously decrease, for all substitute ratios, with 33.3% for SR = 9, with 59.7% at SR = 18, with 69% at SR = 27 and with 73.8% for maximum SR = 34, comparative to classic fuelling, due to reduction of the carbon content.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

The data that has been used is confidential.

Declaration of interest's statement

The authors declare no conflict of interest.

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