A NUMERICAL SIMULATION OF THE INFLUENCE OF INJECTION CHARACTERISTICS ON PERFORMANCE AND EMISSIONS OF A TRACTOR DIESEL ENGINE

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Studiul urmăreşte tendinţele de modificare a performanţelor şi emisiilor unui motor diesel de tractor la modificarea structurii legii de injecţie când motorul este alimentat în mod dual, folosind programul de simulare AVL Boost v2009.1. Modelul creat simulează funcţionarea unui motor diesel prevăzut cu un sistem suplimentar de alimentare folosit pentru mici adaosuri de hidrogen. Studiul compară rezultatele obţinute pentru legii de injecţie modificate, motorul operând cu motorină plus două debite de hidrogen (13.2 l/min şi 19.8 l/min) introduse în aerul aspirat în cilindru.

The study investigates the influence of the modified injection timing on performance and exhaust emissions of a tractor diesel engine fueled in dual mode. The study was conducted using AVL Boost simulation program. The numerical code simulates the engine operating with an extra fueling system used for small amounts of hydrogen. The results obtained for different injection timings and two hydrogen flow rates (13.2 l/min and 19.8 l/min) aspirated in the air stream inducted in the cylinder are analyzed and compared.

Keywords: diesel engine, dual fueling, hydrogen, injection timing, performance, emissions

1. Introduction

The numerical simulation is a mean to calculate a physical phenomenon or to evaluate its tendency. Nowadays, the simulation codes have become indispensable in the research area activity ensuring a considerable decreasing of costs and execution time.

Simulations of phenomena occurring in the internal combustion engines were developed in many different types of software programs. The difference between them is given by the complexity of representing the real behave of the engine. The resulting model is finally corrected based on available experimental data and then is used to analyze or predict tendencies.

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The existing codes simulate the processes within cylinder (gas flow, air-fuel mixing, combustion and heat transfer) intake and exhaust systems (gas flow phenomena) fuel-injection systems (fuel flow and injection phenomena) etc., in specific conditions imposed by the details of the engine component design and operation conditions [1]

The current work is using AVL Boost code, 2009.1 version.

The purpose of this study is to emphasize the influence of modifying the injection timing on the behaviour of a tractor diesel engine, 3.7 liters, naturally aspirated, when operates with diesel fuel and small amounts of hydrogen added in the intake manifold. The evolution of exhaust emissions and brake thermal efficiency were analyzed.

2. Model calibration and test procedure

Fig. 1 shows the symbolic scheme of the engine. The model is composed by several pipes (1-18), manifolds (Plenum, PL1-PL3), junctions (J1-J5), air filter Cl1, cylinders (C1-C4), measuring points (MP1-MP5). There are also taken into account the ambient conditions by surroundings parameters (System Boundary SB1-SB4).

A hydrogen injector I1 is placed on the air flow line in order to simulate the enrichment of the intake air with small amounts of hydrogen. Every part of the scheme has established properties related to dimensions or parameters values which are identical to those form the test cell.[2]

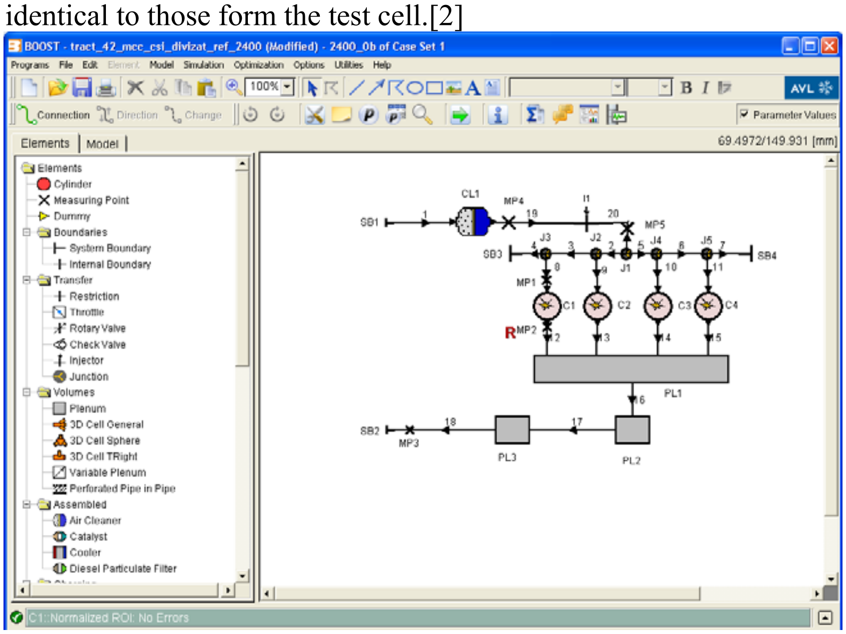

Fig. 1 – The symbolic model of the engine

The flow processes through the pipes or manifolds are calculated with a one-dimensional model by mathematic equations. The cylinders are considered identic and they change continuosly heat and energy with the pipes. Beside the general data regarding the fuel properties and the type of mixture forming (figure 2) there are also introduced the technical data of the cylinder: bore, stroke, compression ratio, etc – Fig. 3.

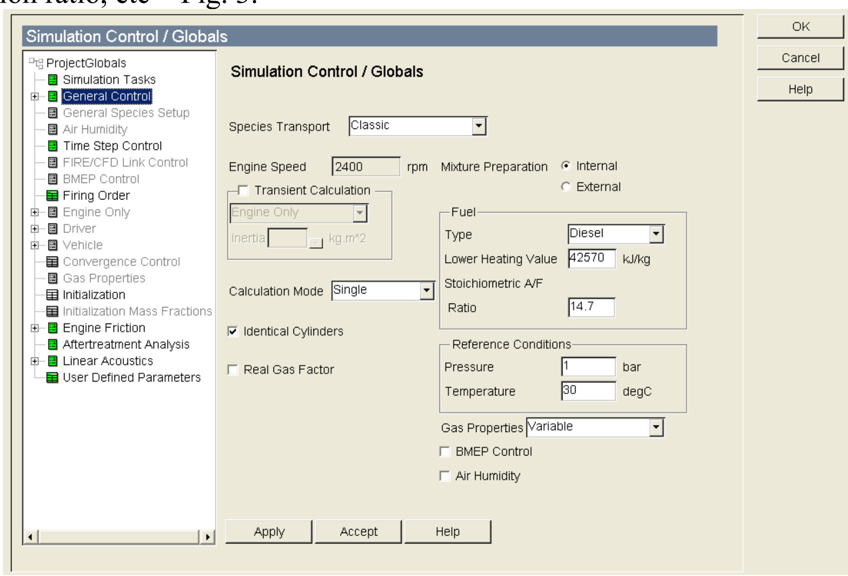

Fig. 2 – Fuel initialization

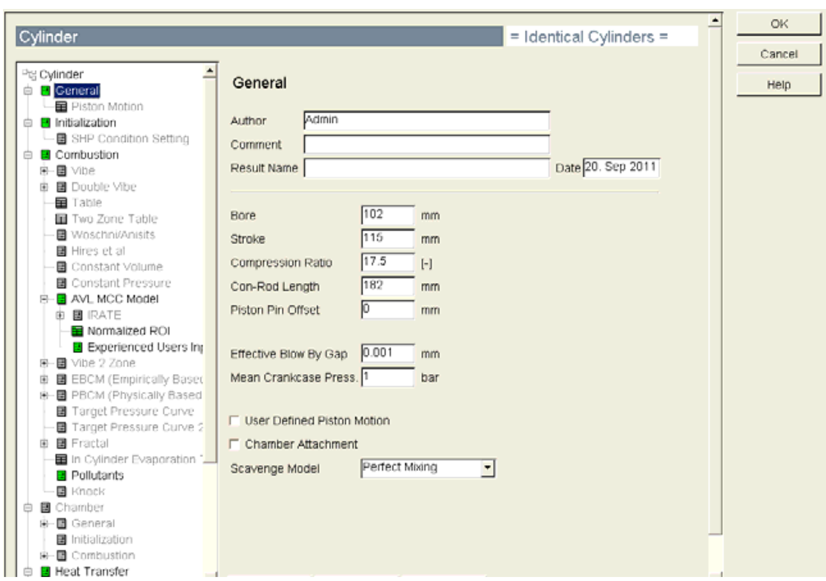

Fig. 3 – Technical data of the cylinder

The enrichment of the inducted air stream in cylinder is simulated by the continuous flow of hydrogen through the special gas injector I1 (figure 1). The mixing ratio of the fuels is specified by the mass percentages of diesel fuel and hydrogen admitted in the cylinder.[3]

A first step, before starting the simulations, is represented by the calibration of the model. The calibration is assuming that the results obtained in simulation are very close to those measured in the test cell. Hence, the main objective is to correlate the pressure diagrams but also to consider other parameters like: brake power, brake effective torque, air or fuel consumption, air flow-ratio, temperatures, pressures, etc.

The current study studies the influence of modifying injection characteristics on the engine performance. Considering this, the test facility was equipped with needle lift and pressure line sensor, so the real injection timing was determined. In the section defining injection parameters the normalized rate of injection, which is the rate of injection divided by the fuel amount per cycle and cylinder was introduced – Fig. 4. [4]

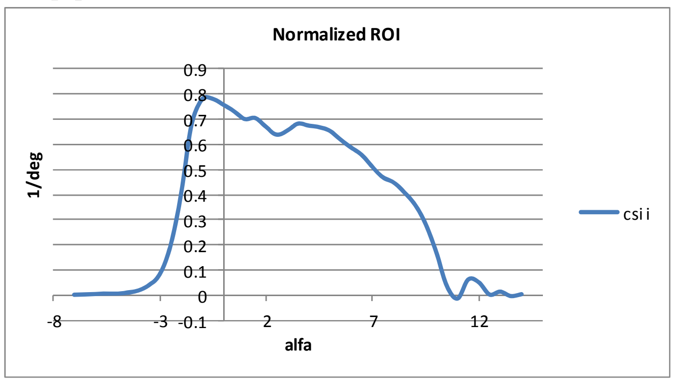

Fig. 4 – Normalized rate of injection

Having all these parameters, the model can be calibrated. As mentioned before, the main purpose of calibration is to obtain an almost similar pressure diagram for the AVL code in comparison with experimental results.[5]

First, the model was calibrated on regular diesel fuel, at a specified operating condition of 2400 rpm (the maximum speed at nominal power), 60% load (part load) and constant power condition. After calibration, the model was used for two flow rates of hidrogen: 13.2 liters/min and 19.8 litres/min.

The results of calibration stage are shown in Figs. 5, 6 and 7.[6]

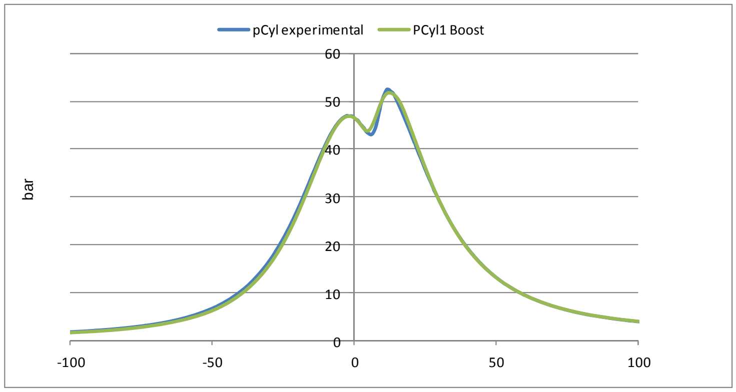

Fig. 5 – Pressure traces comparison for calibration on diesel fuel

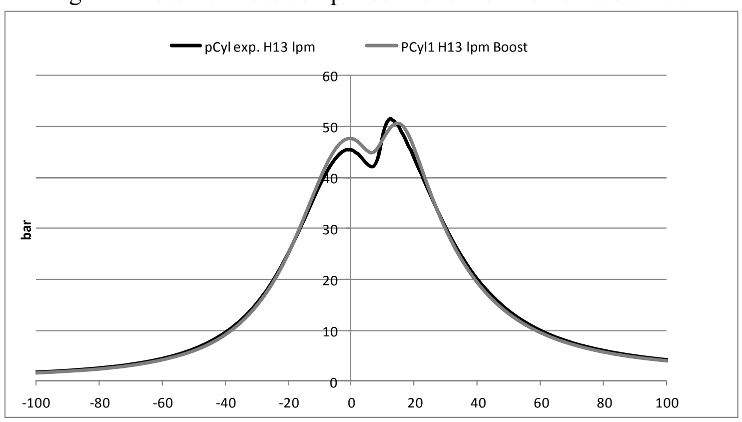

Fig. 6 – Pressure traces comparison for calibration on diesel fuel + 13.2 liters/min hydrogen

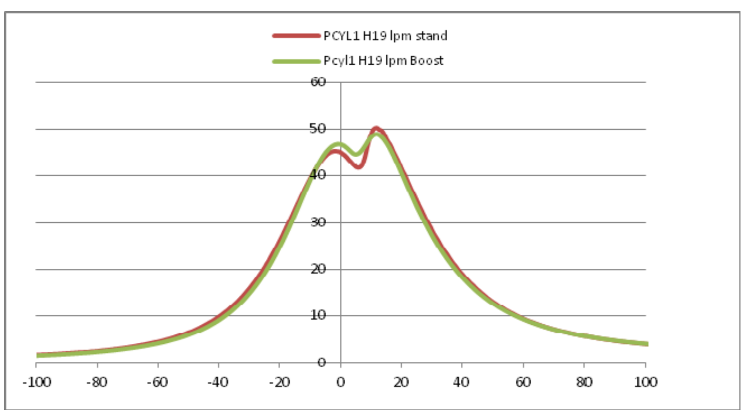

Fig. 7 – Pressure traces comparison for calibration on diesel fuel + 19.8 liters/min hydrogen

The calibration errors are summarized in tabel 1:

Table 1

Calibration errors

	Diesel fuel					
	P	**M**	**p_max**	**NOx**	**CO**	**bsfc**
	kW	**Nm**	**bar**	**g/kWh**	**g/kWh**	**g/kWh**
AVL	27.18	108.16	52.4	6.4	6.6	281
Exp.	26.85	106.8	51.6	6.43	6.2	285
Error %	1.23	1.27	1.55	-0.47	6.45	-1.40
	Diesel fuel+13.2 Liters/min H2					
	P	**M**	**p_max**	**NOx**	**CO**	**bsfc**
	kW	**Nm**	**bar**	**g/kWh**	**g/kWh**	**g/kWh**
AVL	26.89	107.01	50.85	6.2	5.7	279.2
Exp.	26.85	106.8	51.3	6.53	6.2	281
Error %	0.14	0.19	-0.87	-5.05	-8.06	-0.64
	Diesel fuel+19.8 Liters/min H2					
	P	**M**	**p_max**	**NOx**	**CO**	**bsfc**
	kW	**Nm**	**bar**	**g/kWh**	**g/kWh**	**g/kWh**
AVL	27.18	108.16	50.62	6.1	4.7	286
Exp.	26.85	106.8	49.6	6.4	5.8	275
Error %	1.22	1.27	2.05	-4.68	-18.96	4

Since the model was calibrated, the next step was to split the injection characteristic of the diesel fuel in two stages: pilot and main injection. The tests were therefore carried out with the following variations: the timing of the pilot was kept constant at 9^o CA and the duration of the pilot has varied from 2.5^o CA to 4.5^o CA with a resolution of 1^o CA; the main injection had a constant duration and the advance of the main injection was varied from 2^o CA to 4^o CA – Fig. 8.

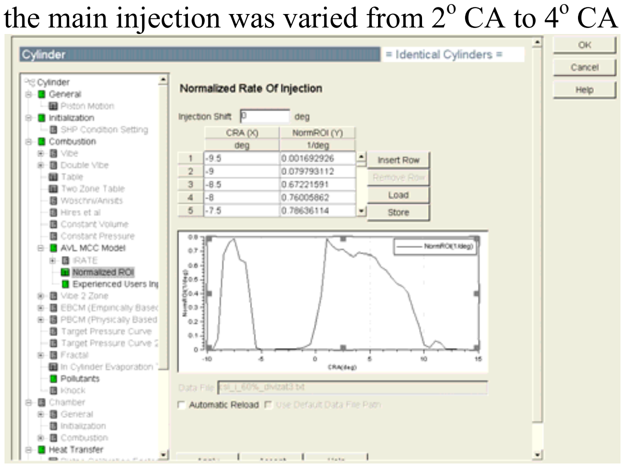

Fig. 8 – Injection divided in two stages

3. Results

The simulated tests were performed at 2400 rpm, 60% load, constant power conditions. In figures 9 – 14 are shown the differences between the normal injection and a case of divided injection regarding the brake thermal efficiency exhaust emissions and for the three versions of fueling (pure diesel, diesel + 13.2 liters/min hydrogen and diesel + 19.8 liters/min hydrogen).

The results are summarized in tabel 2

Table 2

Simulation results

Condition	Diesel						
	P kW	M Nm	BTE %	p_max bar	NOx g/kWh	CO g/kWh	Smoke g/kW
Normal injection, adv 7	27.18	108.16	30.1	50.02	6.4	6.6	0.7
Divided inj., pilot 4.5 deg,	27.34	108.7	30.2	53	7.4	5.73	0.73
Divided inj., pilot 4.5 deg,	26.6	105.8	29.3	49.53	6.9	6.26	0.78
Divided inj., pilot 4.5 deg,	26.61	105.9	29.4	49.06	7	6.27	0.78
Divided inj., pilot 3.5 deg,	27.3	108.73	30.1	53.04	7.8	5.9	0.73
Divided inj., pilot 3.5 deg,	26.89	106.99	29.7	51.1	7.28	6	0.77
Divided inj., pilot 4.5 deg,	26.53	105.57	29.3	49.47	6.9	6.2	0.79
Divided inj., pilot 2.5 deg,	26.36	104.87	29.1	48.64	6.5	6.2	0.79
Divided inj., pilot 2.5 deg,	25.95	103.2	28.6	47.07	6.1	6.4	0.79
Divided inj., pilot 2.5 deg,	25.57	101.74	28.2	45.85	5.7	6.7	0.78
Condition	Diesel+13.2 Liters/min H2						
	P kW	M Nm	BTE %	p_max bar	NOx g/kWh	CO g/kWh	Smoke g/kWh
Normal injection, adv 7	26.89	107.01	29.2	50.85	6.2	5.7	1.02
Divided inj., pilot 4.5 deg,	27.04	107.6	29.4	53.26	6.16	5.2	1.01
Divided inj., pilot 4.5 deg,	27.05	107.6	29.4	53.28	6.1	5.22	1.01
Divided inj., pilot 4.5 deg,	26.24	104.4	29.4	49.81	6.4	5.8	1.04
Divided inj., pilot 3.5 deg,	27.03	107.57	29.5	53.21	6.5	5.4	1.01
Divided inj., pilot 3.5 deg,	26.61	105.89	29.2	51.42	6.43	5.4	1.04
Divided inj., pilot 4.5 deg,	26.2	104.3	28.9	49.76	6.41	5.8	1.04
Divided inj., pilot 2.5 deg,	26.18	104.2	28.9	49.6	6.35	5.78	1.04
Divided inj., pilot 2.5 deg,	25.7	102.3	28.7	48.2	6.3	6.1	1.01
Divided inj., pilot 2.5 deg,	25.3	100.6	28.4	47.7	6.2	6.5	0.96
Condition	Diesel+19.8 Liters/min H2						
	P kW	M Nm	BTE %	p_max bar	NOx g/kWh	CO g/kWh	Smoke g/kWh
Normal injection, adv 7	27.18	108.16	28.5	50.62	6.1	4.7	1.01

Divided inj., pilot 4.5 deg,	27.41	109.05	29.5	53.19	6.02	4.33	0.98
Divided inj., pilot 4.5 deg,	27.01	107.46	29.1	51.77	6.36	4.57	1.01
Divided inj., pilot 4.5 deg,	26.57	105.73	29.0	50.25	6.49	4.87	1.02
Divided inj., pilot 3.5 deg,	27.4	109.02	29.0	53.13	6.42	4.49	0.98
Divided inj., pilot 3.5 deg,	26.98	107.36	29.3	51.8	6.38	4.57	1.01
Divided inj., pilot 4.5 deg,	26.55	105.6	29.0	50.2	6.49	4.88	1.02
Divided inj., pilot 2.5 deg,	26.62	105.6	29.0	49.97	6.4	4.8	1.02
Divided inj., pilot 2.5 deg,	26.06	103.7	28.8	48.4	6.35	5.1	0.98
Divided inj., pilot 2.5 deg,	25.64	102.03	28.5	47.8	6.25	5.4	0.93

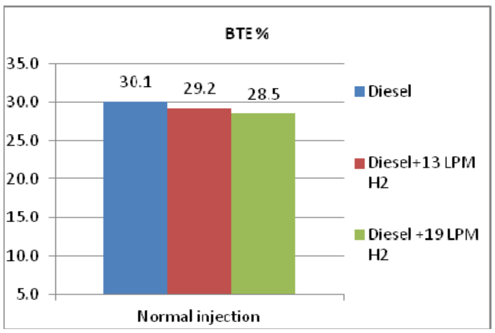

Fig. 9 – BTE with normal injection

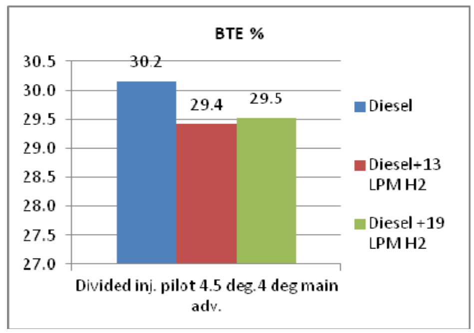

Fig. 10 - BTE with divided injection

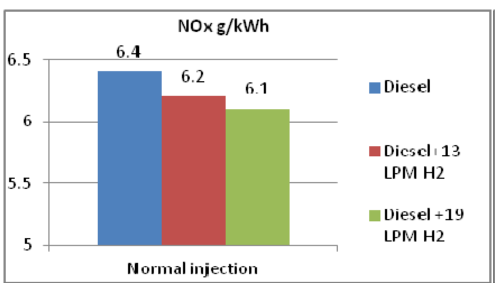

Fig. 11 – NO_x emission with normal injection

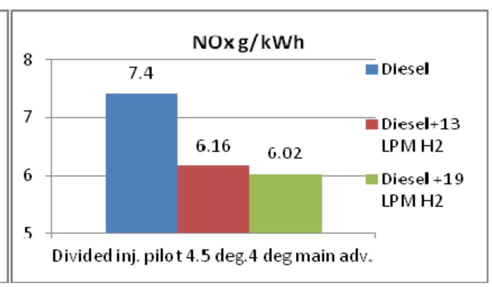

Fig. 12 – NO_x emission with divided injection

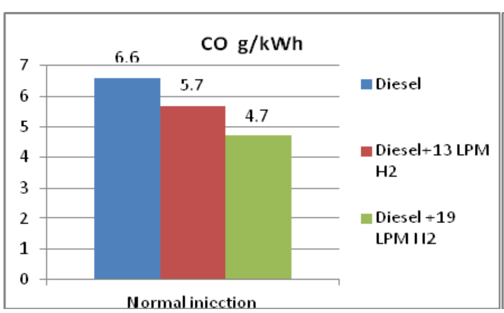

Fig. 13 – CO emission with normal injection

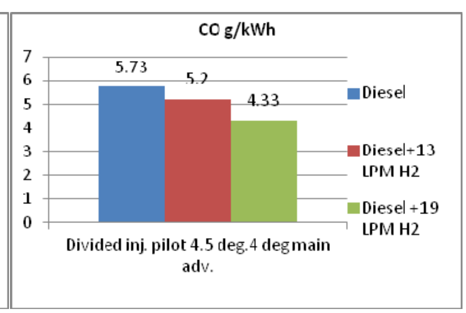

Fig. 14 – CO emission with divided injection

The results showed almost the same level of NO_x emissions for both types of injection, excepting the case of operating with pure diesel where NO_x emission was increased with 15%; CO emission was smaller by about 13% for divided injection; the smoke level did not show significant changes; the brake thermal efficiency was higher, up to 3% for divided injection.

In figs. 15 – 17 are ilustrated comparisons of emissions and brake thermal efficiency for the same fuel but for different injection timings. All the comparisons are related to the base reference which is diesel fuel and unsplited injection.

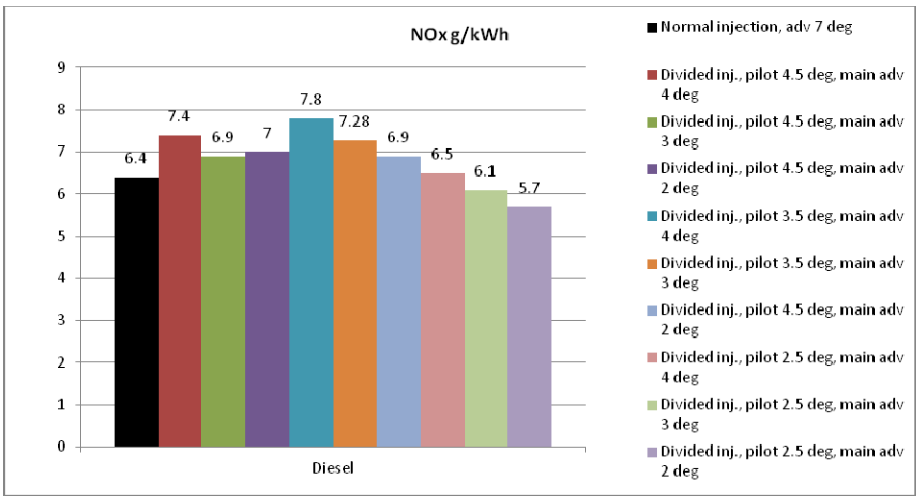

Fig. 15 – NO_x emission for diesel fuel at diferent injection timings

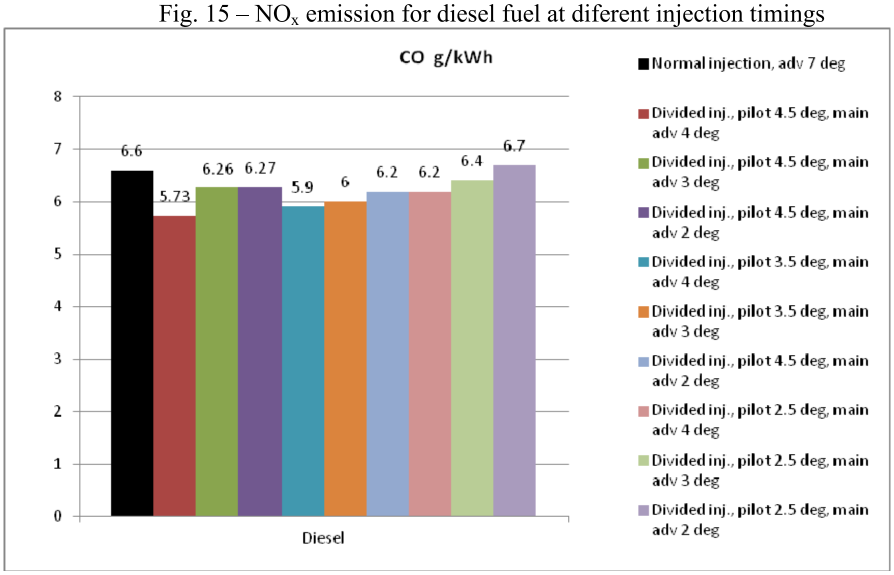

Fig. 16 – CO emission for diesel fuel at diferent injection timings

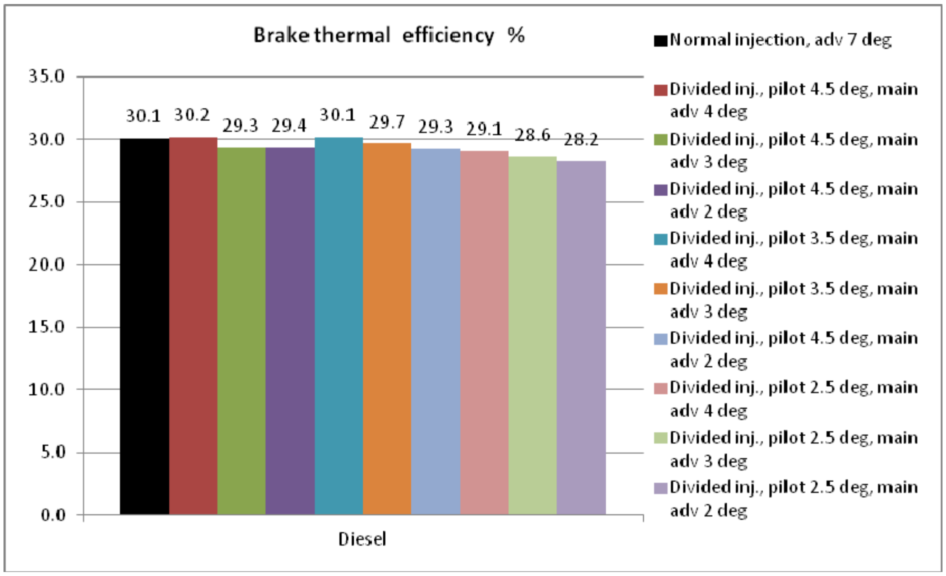

Fig. 17 – BTE for diesel fuel at diferent injection timings

These results show that the strategy of modifying the injection timing can improve the engine brake thermal efficiency when opperates on diesel fuel and 19.8 liters/min of hydrogen, by a maximum of 3.7% for a pilot of 4.5 degree duration and main injection with an advance of 4 degree; the NO_x emission for diesel fuel decreases by a maximum of 11% when a pilot of 3.5 degree and a main of 4 degree advance are used; the CO level decreases by a maximum of 8% for pure diesel when a pilot of 4.5 degree and an advance of 4 degree for the main injection is used.

There are also some drawbacks to be mentioned. The short pilot injection produces a penalty of 5-15 % on smoke emission for all fuels considered and also a decrease of 10% in engine performance.

4. Conclusions

The present study leads to the following conclusions:

1. The addition of hydrogen decreases generally the level of CO and NO_x emission by 30% and 18% respectively, for any type of injection, the brake thermal efficiency decrease slightly by 2%.
2. The variations of injection timing produce diferent tendencies related to the pilot duration or the advance of the main injection, thus the study reports tendencies of increasing brake thermal efficiency for

pilots with longer duration and lower emissions for pilots with short duration.

3. The final conclusion could be that the injection characteristics offer a real possibility to optimize the diesel engine operation according to manufacturer targets.

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