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NUMERICAL STUDY ON INJECTION TIMING FOR REDUCED EMISSIONS FROM AN ENGINE OPERATING WITH DIESEL OIL AND HYDROGEN

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Abstract. *The present study uses the AVL BOOST software to simulate a compression ignition engine fuelled by diesel oil and hydrogen and verify the influence of diesel oil injection timing variation on exhaust emissions. The combustion model requires input data which characterize the injection process, such as injector hole diameter, injection pressure in the fuel line and flow coefficients. The model was validated against experiments carried out in a naturally-aspirated, four-stroke, four-cylinder diesel engine, of 50 kW maximum power. The engine was operated with varying load from 0 kW to 40 kW, at the speed of 1800 rpm, and using hydrogen as a replacement fuel to diesel oil at mass-based concentrations of 5%, 10% 15% and 20%. Hydrogen was injected in the intake manifold, while diesel oil was directly injected in the combustion chamber. The results show that advancing diesel oil injection timing over 4 crankshaft degrees leads to a slowly increase of oxides of nitrogen (NO_X) emissions. Nearly the same behavior is presented by carbon monoxide (CO) emission with variation of injection timing. For soot emission there is a slight reduction for an advance of injection timing up to 10 crankshaft degrees.*

Keywords: *Hydrogen, diesel engine, emissions, injection timing.*

1. INTRODUCTION

The use of hydrogen (H_2) as an alternative fuel for internal combustion engines has extensively been analyzed in recent years. Hydrogen consists of a chemical element widely available in nature that can be obtained from water, for example. Its combustion process is clean, generating only steam (Almeida, 2012). Several studies have been developed on the analysis of the performance of engines operating with diesel-hydrogen mixtures. Shin *et al*. (2011), SinghYadav *et al.* (2012) and Bose *et al.* (2009) obtained the reduction of carbon monoxide (CO) and carbon dioxide (CO_2), oxides of nitrogen (NO_X) and hydrocarbon (HC) emissions using diesel oil-hydrogen blends in a diesel engine with exhaust gas recirculation (EGR). Miyamoto *et al.* (2011) investigated the injection timing variation, which resulted in combustion temperature decrease and, therefore, a reduction of NO_X and soot emissions. Birtas *et al.* (2011) noticed that a small amount of hydrogen with EGR can be used on a tractor diesel engine with favorable effects on emissions and a small penalty on efficiency.

According to Bari *et al.* (2010) H_2/O_2 mixtures can also be used in internal combustion engines, resulting in increased thermal efficiency and reduced brake specific fuel consumption (SFC). In addition, emissions of HC, CO_2 and CO were found to be reduced. Antunes *et al*. (2009) noticed that the use of hydrogen direct injection in a diesel engine produces higher power and a significant efficiency advantage as well as a reduction on nitric oxide (NO) emissions. According to Liu *et al*. (2011) the addition of 2% and 4% of H_2 in a heavy-duty diesel engine operating with dual fuel combustion increased significantly the emissions of nitrogen dioxide (NO_2), compared to NO and NO_X emissions. Experiments in a spark ignition engine fuelled by hydrogen and gasoline were performed by Ganesh *et al*. (2012). An improvement on brake thermal efficiency was observed for hydrogen operation; however gasoline operation produced higher maximum brake power output. Huang *et al*. (2007) evaluated the performance of a direct-injection spark-ignited engine fuelled by natural gas–H_2 blends. The amount of heat release decreased with the increase of H_2 fraction in the fuel blends and HC emissions decreased with advancing ignition timing. An increase of NO_X emissions was observed.

The application of computer simulation for engine performance analysis enables to obtain fast and reliable results. Park *et al*. (2011) analyzed an engine employed to power a generator fuelled by methane and hydrogen blends, using DOE (Design of Experiments) method and a cycle simulation tool GT – POWER. Heat released rate, cylinder temperature and pressure increased with the addition of amounts of hydrogen. Methane and hydrogen blends were also investigated by Ceper *et al*. (2009), which obtained a reduction on HC, CO and CO_2 emissions with the increase of hydrogen in the blend. Lilik *et al*. (2010) conducted a computational fluid dynamics analysis (CFD) based on Reynolds

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governing equations which increased soot and HC formation and reduced CO and CO_2 emissions. Lata and Misra (2010) investigated the performance of a dual fuel engine operated on diesel, hydrogen and liquefied petroleum gas (LPG), resulting in a brake thermal efficiency about 3% and 4% less than experimental results.

Carvalho (2011) developed a computational tool for the exergetic analysis of cogeneration systems powered by internal combustion engines which consists in an integrated model that couples an engine simulator to a process simulator. Softwares SimTech IPSEpro were selected for thermal plant simulation and the software AVL BOOST was used for internal combustion engine modeling. The results showed that emissions are the main barrier to the maximization of the efficiency. AVL BOOST was also used by Melo (2012) to study different hydrous ethanol and gasoline blends influence on a flexible fuel engine performance. Almeida (2012) performed simulations with the same software to evaluate performance and exhaust concentration of pollutant components from a stationary diesel engine. The results indicated a reduction of specific fuel consumption and pollutant emissions.

This paper aims to study the influence of diesel oil injection variation on exhaust emissions from a compression ignition engine fuelled by diesel oil and hydrogen. For this, AVL BOOST was selected to perform the simulations and geometry and operation data were given as program input to characterize the injection process. NO_X, CO and soot emissions are evaluated. Diesel oil was directly injected in the combustion chamber while hydrogen was injected in the intake manifold at mass-based concentrations of 5%, 10% 15% and 20%. Diesel fuel injection timing ranged from 0 to 10 crankangle degrees before top dead center (BTDC).

2. NUMERICAL METHODOLOGY

In this study the AVL BOOST software was used as a tool to perform the simulations. With this software it is possible to simulate a wide variety of engines - 4-stroke or 2-stroke, spark or compression ignited, small capacity engines up to large engines for marine propulsion - enabling the characterization of combustion processes, emissions and heat transfer. The program also allows for the representation of the examined engine through a graphical interface, simulating all the possible elements. The flow in the pipes is treated as one-dimensional, which means that pressure, temperature and speed obtained by the gas dynamic equations are the main values for pipe characterization (AVL Users Guide, 2010). To perform the simulations, a model of internal combustion engine was represented using symbols of AVL BOOST graphical user interface. The main elements of the representation are detailed in Tab. 1 and Fig. 1.

Table 1. Main engine elements used in graphic representation

ELEMENT	QUANTITY	SYMBOL
Engine	1	E
Cylinder	4	C
Injector	1	I
System boundaries	2	SB
Plenums	3	PL
Junctions	3	J
Measuring points	14	MP

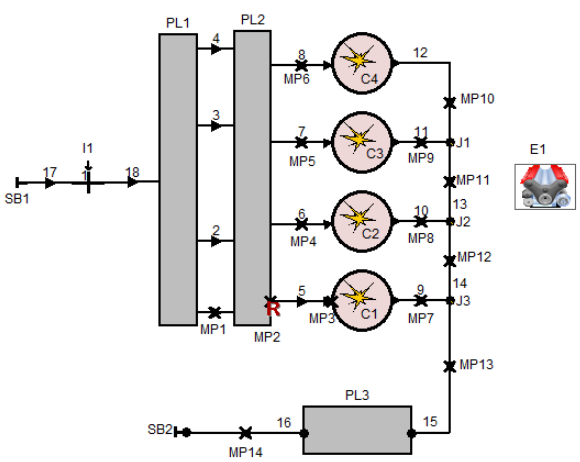

Figure 1. Engine graphic representation

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Engine speed, cycle type, cylinder setup and the firing order were used as input to the program as shown by Tab. 2. Four identical cylinders were considered and the firing order was based on MWM INTERNATIONAL engines manual (Almeida, 2012).

Table 2. Engine input data

PARAMETER	VALUE
Engine speed	1800 rpm
Cycle type	4 Stroke
Cylinder setup	Identical cylinders
Firing order	1st cylinder: 0° 2nd cylinder: 540° 3rd cylinder: 180° 4th cylinder: 360°

Cylinders are the most important part of the system and require geometry, combustion, pollutants and heat transfer data. Table 3 presents geometric data provided by MWM INTERNATIONAL engines manual. The scavenge model follows a 4 strokes engines standard model (AVL Users Guide, 2010).

Table 3. Engine geometry data

PARAMETER	VALUE
Bore	102 mm
Stroke	120 mm
Compression ratio	17 mm
Connecting rod length	207 mm
Piston pin offset	0 mm
Effective blow by gap	0.0008
Mean crankcase pressure	1bar
Scavenge model	Perfect mixing

To characterize the engine combustion process the software offers different options to obtain the heat release, Single Vibe Function, Double Vibe Function, Woschni/Anisits (only mixtures prepared internally) (Hires *et al.*, 1978) for mixtures prepared externally and AVL MCC (Mixing Controlled Combustion) (AVL Users Guide, 2010). In this study the AVL MCC model was used to simulate the variation of injection timing. This model allows for a projection of the rate of heat release and NO_X production in diesel engines based on the amount of fuel in the cylinder and on the kinetic energy introduced by the fuel (AVL Users Guide, 2010). The number and diameter of the injector holes, rail pressure and discharge coefficients were given as input to the combustion model, as indicated in the Tab. 4.

Table 4. Input data of AVL MCC Model

PARAMETER	VALUE
Number of injector holes	4
Hole diameter	0.25 mm
Discharge coefficient	0.5
Rail pressure	1500 bar

The main parameters of pollutant emissions model are presented in Tab. 5. NO_X production model is based on Pattas and Häfner (1973) and needs a NO_X kinetic multiplier and NO_X post processing multiplier values. CO production is based on Onorati *et al.* (2001) model and only one production parameter needs to be determined. In the case of soot production the software uses the model by Schubiger *et al*. (2002), and requires production and consumption parameters (AVL Theory, 2010).

In case of heat transfer, Woschini (1990) model was chosen requiring insertion of the surface, wall temperatures and calibration factor of piston, cylinder head and liner. All the values were obtained from MWM INTERNATIONAL engines manual (Almeida, 2012) as indicated in Tab. 6. In the table, TDC means top dead center and BDC bottom dead center.

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Tab 5. Pollutants production model input data

PARAMETER	VALUE
NO_X production model	
NO_X kinetic multiplier	1
NO_X post processing multiplier	0.64
CO production model	
CO kinetic multiplier	1
Soot production model	
Soot production constant	1000
Soot consumption constant	775

Table 6. Heat transfer model input data

PARAMETER	VALUE
Cylinder	Woschini (1990)
Piston surface area	11.400 mm^2
Piston wall temperature	400°C
Piston calibration factor	1
Head surface area	8171 mm^2
Head wall temperature	360°C
Head calibration factor	1
Liner surface area (piston at TDC)	101 mm^2
Liner wall temperature (piston at TDC)	360°C
Liner wall temperature (piston at BDC)	350°C
Liner calibration factor	1

2.1 Injection Timing Variation

The simulation input data were obtained from experimental procedures performed by Morais *et al*. (2013). The tests were carried out using a naturally-aspirated, four-stroke, four-cylinder diesel engine made by MWM Motores Diesel Ltda. It works with a mechanically-controlled and a direct injection fuel system. The main specifications of this engine are mentioned in Tab. 7 (Almeida, 2012).

Table 7. Engine parameters

PARAMETER	TYPE OR VALUE
Manufacturer	MWM
Model	D229-4
Serial number	B1N426219
Construction type	Diesel – 4 strokes in line
Injection time	Direct
Bore × stroke	102 mm × 120 mm
Number of cylinders	4
Piston displacement per unity	0.980 liters
Total piston displacement	3.922 liters
Aspiration	Natural
Speed	1800 rpm
Power	44 kW (60 hp)

The amount of hydrogen injection was based on the results obtained by Morais *et al*. (2013). The engine was operated with varying load from 0 kW to 40 kW at the speed of 1800 rpm. Hydrogen was used in different mass – based concentrations as a replacement to diesel oil: 0% (B5H0), 5% (B5H5), 10% (B5H10), 15% (B5H15) and 20% (B5H20). Tab. 8 presents the injected fuel amounts at 0 kW and 40 kW.

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Table 8. Amount of hydrogen injected

LOAD	HYDROGEN MASS FLOW RATE (kg/h)				
(kW)	B5H0	B5H5	B5H10	B5H15	B5H20
0	0	0.035	0.071	0.106	0.141
40	0	0.173	0.347	0.488	0.693

Heating values of 43,200 kJ/kg and 119,900 kJ/kg hydrogen were considered in the program calculations for diesel oil and hydrogen, respectively. The injection timing varied from 0 to 10 crankshaft degrees, and the values were added from the creation of a specific parameter in the model used for combustion.

3. RESULTS AND DISCUSSION

Simulations were performed using software AVL BOOST and NO_X, CO and soot emissions were obtained. Hydrogen has a higher ignition delay due to its higher octane number and spontaneous ignition temperature, of nearly 580°C, which is higher than that of diesel oil. Ignition delay influences combustion stability, brake thermal efficiency and emissions, resulting in lower performance of a diesel engine (Masood *et al.*, 2007). According to Lata and Misra (2011) ignition delay depends on fuel concentration and type, load conditions, intake manifold pressure and temperature and oxygen concentrations of a dual fuel engine.

Figure 2 presents NO_X emissions variation with diesel oil injection timing and hydrogen concentration. The NO_X formation depends mainly on hydrogen concentrations and temperatures in the combustion zone (Melo, 2012). Advanced injection timing resulted in NO_X emissions increase. An increase in hydrogen concentrations resulted in NO_X emissions decrease, especially at more advanced diesel oil injection timing.

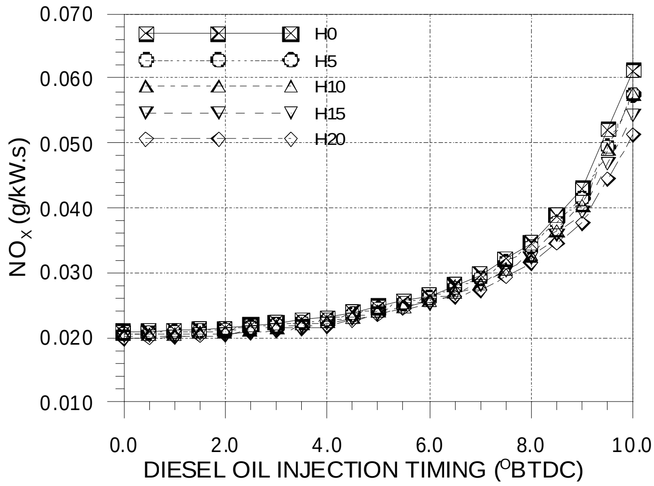

Figure 2. NO_X emissions with variation of injection timing and hydrogen amount

Similar results were obtained by Massod *et al*. (2007), who analyzed the effect of direct injection of hydrogen into the combustion chamber and H_2 induction through the inlet manifold using FLUENT software. The NO_X formation in case of the induction method was found to be higher than that of the direct injection method. Injection timing advance increased pollutant concentrations and had the maximum value near 23°BTDC. The increase of NO_X emissions with injection timing advance was also noticed by Adnan *et al.* (2009). According to the authors, this occurred due to temperature increase in the combustion chamber, resulting in higher nitrogen oxidation rate.

CO emissions had a similar behavior as NO_X emissions, increasing with advanced injection timing, as indicated by Fig. 3. CO emissions decrease with increased hydrogen concentration, especially at advanced injection timing. Masood e Ishat (2008) conducted simulations for determining the mole fraction of exhaust species when hydrogen is burnt along with diesel. The author noticed that, as the mixture gets richer, the mole fraction of CO increases due to incomplete combustion of carbon. As the temperature increases CO_2 dissociates to form CO. Adnan *et al*. (2009) also obtained in their studies an increase of CO emissions due to the high pressure and temperature during the combustion process.

A reduction of soot emissions can be observed with advanced diesel injection timing, reaching a minimum value between 8-9°BTDC, as indicated by Fig. 4. The addition of hydrogen to diesel fuel decreased soot emissions. A study developed by An *et al*. (2013) also resulted in soot emissions reduction by the use of hydrogen. The engine was operated at 1600, 2400 and 3200 rpm and using different concentrations of hydrogen. Soot emissions were shown to be reduced under most of the engine operating conditions due to the lack of carbon in H_2 composition.

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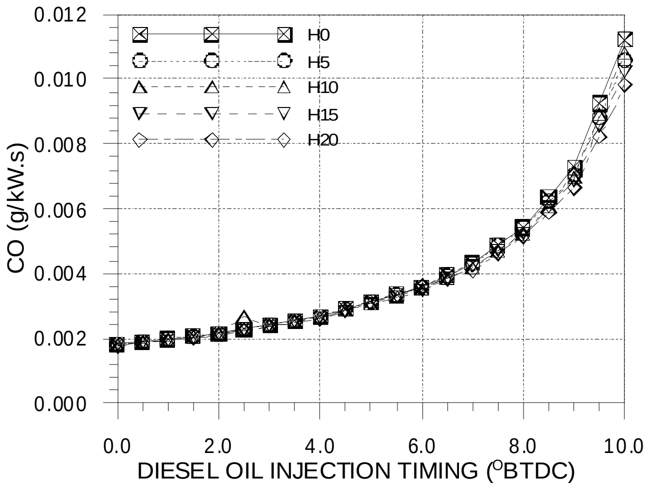

Figure 3. CO emissions with advancing injection timing and different amounts of hydrogen

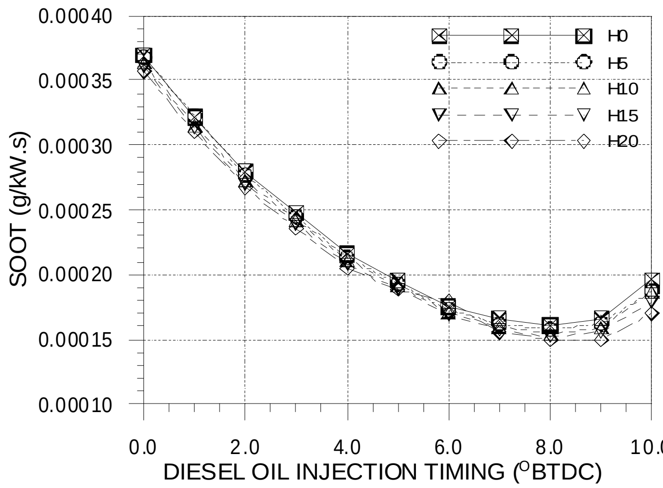

Figure 4. Soot emissions with advancing injection timing and different amounts of hydrogen

4. CONCLUSION

This paper presents computational simulations performed using AVL BOOST software to verify the influence of diesel oil injection variation on exhaust emissions of a compression ignition engine fuelled by diesel oil and hydrogen. The input data were obtained from experimental procedures performed by Morais *et al*. (2013). The results show that advancing diesel oil injection timing leads to an increase of NO_X and CO emissions that, according to other authors, can be caused by temperature and pressure increase in the combustion chamber. For soot emission there is a reduction for an advance of injection timing and this result were also obtained in others studies. As hydrogen concentration is increased a reduction of all pollutant emissions investigated was observed.

5. ACKNOLWDGEMENTS

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