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Computational simulation of a diesel generator consuming vegetable oil "in nature" and air enriched with hydrogen

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Abstract
A diesel generator was simulated operating with palm oil as fuel and hydrogen doping the inlet air. The objective was to investigate how the addition of hydrogen can accelerate the end of vegetable oil combustion, and consequently improve the electrical efficiency of the generator set up, for the same mass flow rate of fuel. The simulations were performed using AVL BOOST software and validated with experimental data. The generator was simulated operating with 75%, 80% and 100% of the nominal load using palm oil in nature, and hydrogen being injected at the intake manifold in parcels of 5% to a maximum of 20% in energy content by replacing the main fuel. The simulations showed increase in electrical power, reduction in specific fuel consumption, improving the overall efficiency of the generator set with 100% load. Good results were obtained with operation at 75% of the nominal load.

Keywords: Combustion; Palm Oil; Hydrogen; Diesel Generator; AVL BOOST.

Simulación de un grupo generador diesel consumiendo aceite vegetal "in natura" y aire enriquecido con hidrógeno

Resumen
Simulamos un generador diesel para operar con aceite de palma e hidrógeno como combustibles. El objetivo era investigar cómo la adición de hidrógeno puede acelerar el final de la combustión de aceite vegetal, y en consecuencia mejorar la eficiencia eléctrica del generador, para la misma tasa de flujo de masa de combustible. Las simulaciones fueron realizadas utilizando el software AVL BOOST y validadas con datos experimentales. El generador fue simulado para operar con 75%, 80% y 100% de la carga utilizando aceite de palma natural, y el hidrógeno comenzó a ser inyectado en el colector de admisión en porciones de 5% a 20% que substituían el combustible principal. Las simulaciones mostraron aumento de la potencia eléctrica, reducción en el consumo específico de combustible y mejora de la eficiencia global de la operación del conjunto generador a una carga de 100%. Resultados satisfactorios de funcionamiento se obtuvieron con carga del 75%.

Palabras clave: Combustión; Aceite de Palma; Hidrógeno; Generador Diesel; AVL BOOST.

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1. Introduction

The regions of the humid tropics, especially the Amazon, are rich in oil palms that produce vegetable oils, many without a commercial value. These same regions are dependent on petroleum for their energy supply, either to generate electricity, heat or land and fluvial transportation, where the logistics to guarantee the supply of fossil fuels are complex and expensive. According to [1], "the challenge for any country or region is the implementation of processes of production based on feedstock, with local availability." For the author, "these processes should be optimized with the goal of getting biofuels with competitive production costs and an appropriate quality." An example of this is that vegetable oils are capable of being used as hydrocarbon fuel with the advantage of being renewable and promote local economies. Research with this focus is required as an alternative to decreasing dependence on fossil fuels, mainly oil, natural gas and coal, whose total primary energy consumption grew by 1.8% in 2012 relative to 2011 [2]. In this context, the use of

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vegetable oil *in natura* (VO), that is filtered and degummed only, in internal combustion engines (ICE) as a viable alternative in complete or partial replacement to fossil fuels has been investigated. However, the use of VO in unmodified diesel engines leads to a reduction of thermal efficiency and increased levels of soot [3]. As a proposal to make the use of VO feasible, researchers are introducing other types of fuels as an additive to vegetable oil. [3] carried out performance experiments in a compression ignition engine using vegetable oil from Jatropha plus small quantities of hydrogen (H_2) as the main fuel, which led to an improvement in the performance of this engine. One of the major advantages to using H_2 as fuel is the absence of carbon in its chemical composition, which means that it has a very high burning rate and, thus, combustion is very fast and its wide range of flammable limits allows use equivalence ratio in the range of 0.1 to 7.1 [4]. The wide flammability of H_2 allows the engines that use it as a fuel to operate with very lean mixtures resulting in greater fuel savings and more complete combustion [5]. Variations in both the injected amount of H_2 as the types of vegetable oil used has been studied. [6] investigated the use of rubber seed oil, methyl-ester rubber seed oil and diesel as main fuels, and H_2 as an inductor, and concluded that there was a decrease in peak pressure in the cylinder with the addition of H_2, in addition to an increase in the rate of combustion due to an improvement in the rate of heat release. Following this line of research, this study aimed to simulate the operation of a diesel generator, which occurred without changes in the ICE geometry, and only varying their operational parameters, using palm oil *in natura* as the main fuel and the addition of small amounts H_2 by the intake manifold. The commercial software used was the AVL BOOST, employed by several authors such as [7], [8], [9] and [10], which confers reliability and speed and guarantees that results are achieved.

2. Numerical Methodology

The software adopted for the simulation was the AVL BOOST version 2011.2, which provides a graphical user interface (GUI) composed of icons that represent components of ICE. Once selected and interconnected, the icons allow to open windows through which the geometrical and operational data of the engine, as well as the mathematical models that make up the simulation are inserted [11]. The numerical model created to represent the ICE is shown in Fig. 1.

Table 1 shows the nomenclature of the majors elements used in the computational model and identified in Fig. 1.

Table 1.
Nomenclature of the majors elements used in the computational model and identified in Figure 1.

Element	Symbol	Quantity
Engine	E	1
System Boundary	SB	2
Measuring Point	MP	7
Air Cleaner	CL	1
Injector	I	1
Plenum	PL	2
Cylinder	C	4

Source: The authors.

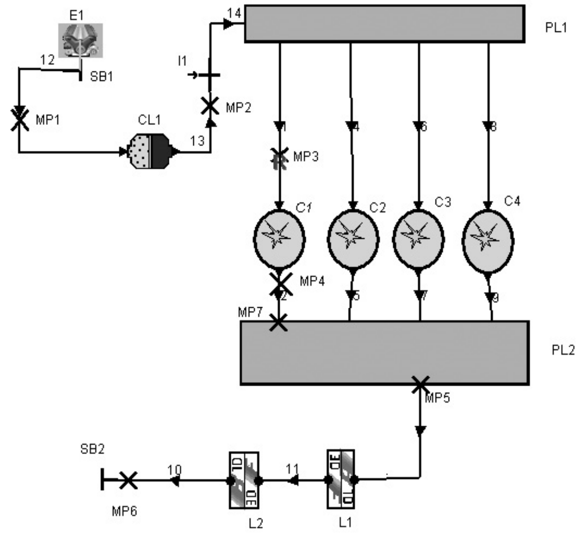

Figure 1. Graphical representation of the model of the internal combustion engine.
Source: The authors.

Geometric and operational parameters used to create the computational model were obtained from a Hyundai, Model D4BB-G1 generator, with maximum power of 20kVA, consisting of a diesel internal combustion engine, naturally aspirated, four-cylinder and indirect injection. The main characteristics of the engine and generator are shown in Table 2.

2.1. Combustion Model

The combustion model considered was Vibe 2 Zone, which specifies the rate of heat release, considering the burned and unburned mass fractions. Thus, the calculation of the thermodynamic state of the cylinder is based on the 1st Law of Thermodynamics, as shown below:

$$\frac{dm_b u_b}{d\alpha} = -p_c \frac{dV_b}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum \frac{dQ_{Wb}}{d\alpha} + h_u \frac{dm_b}{d\alpha} - h_{BB,b} \frac{dm_{BB,b}}{d\alpha} \quad (1)$$

$$\frac{dm_u u_u}{d\alpha} = -p_c \frac{dV_u}{d\alpha} - \sum \frac{dQ_{Wu}}{d\alpha} - h_u \frac{dm_b}{d\alpha} - h_{BB,u} \frac{dm_{BB,u}}{d\alpha} \quad (2)$$

where:
index b: burned zone
index u: unburned zone

Table 2.
Main features of generator set Hyundai D4BB-G1.

Parameters	Value
Bore and stroke of engine	0,911m x 0,100m
Total displacement	2.607×10^{-3} m³
Nominal power at 1800 rev/min	18kVA
Compression ratio	22:1
Fuel injection timing	5° ATDC
Firing order	1-3-4-2
Voltage of Electric Generator	220V
Current of Electric Generator	47A
Frequency	60Hz
Number of phases	3

Source: The authors.

$\frac{d(m.u)}{d\alpha}$ change on the internal energy in the cylinder;

$-p_c \frac{dV}{d\alpha}$ piston work;

$\frac{dQ_F}{d\alpha}$ fuel heat input;

$\sum \frac{dQ_W}{d\alpha}$ wall heat losses;

$h_{BB}.\frac{dm_{BB}}{d\alpha}$ enthalpy flow due to blow-by.

and the term $h_u \frac{dm_B}{d\alpha}$ covers the enthalpy flow from the unburned to the burned zone due to the conversion of a fresh charge to combustion products [12].

2.2. *Scavenging Model*

The scavenging model considers the scavenging efficiency which is defined as the volume of fresh air in the cylinder related to the total cylinder volume, and the delivery ratio which is defined as the total volume of air which entered the cylinder related to the total cylinder volume. In choosing this model, data were entered as shown in Table 3.

For the scavenging model the standard adopted by AVL BOOST for four-stroke engines was maintained, which is Perfect Mixing model, which considers that the gas entering into a cylinder is immediately mixed with the contents of the cylinder, and the gas leaving a cylinder has the same composition as the mixture of the cylinder [11].

2.3. *Heat Transfer Model*

The model chosen for heat transfer from the cylinder to walls of the combustion chamber was Woschni (1978), represented by the following equation [12]:

$$\alpha_w = 130.D^{-0.2}.p_c^{0.8}.T_c^{-0.53}.\left[C_1.c_m + C_2.\frac{V_D.T_{c,1}}{p_{c,1}.V_{c,1}}.(p_c - p_{c,o})\right]^{0.8} \quad (3)$$

where
$C_1 = 2.28 + 0.308.\ c_u/c_m$;
$C_2 = 0.00622$ for IDI engines;
D = cylinder bore;
c_m = mean piston speed;
c_u = circumferential velocity;
V_D = displacement per cylinder;
$p_{c,o}$ = cylinder pressure of the motored engine;
$T_{c,1}$ = temperature in the cylinder at intake valve closing (IVC);
$p_{c,1}$ = pressure in the cylinder at IVC.

Table 3.
General input data in the model of the cylinder.

Parameters	Value
Connecting rod length	0.160m
Piston pin offset	0.0m
Effective blow by gap	$8x10^{-8}$ m
Mean crankcase pressure	$1x10^{5}$ Pa
Scavenge Model	Perfect Mixing

Source: The authors.

2.4. *Pollutants Models*

For the calculation of NOx, CO and soot formation standard models were used implemented in AVL BOOST [12]. The NOx formation model is based on Pattas and Häfner model and takes into account 6 elementary reactions based on the Zeldovich mechanism, utilizing 8 species. The CO formation model is based on the Onorati et al. model and takes into account 2 elementary reactions, utilizing 6 species. The soot formation model is based on the Schubiger et al. model and taken into account 2 elementary reactions: one of formation and another of oxidation.

2.5. *Validation and Simulation Methodology*

After creating the model in AVL BOOST, it was validated with the experimental work [13], with some validation data presented in Table 4.

Table 4 shows that in the validation between simulation and experimental works [13], no significant differences were obtained for Electric Power, Electric Performance and mass flow. Thus, loads were adopted in a generator similar to those used by [13]; that is, 75%, 80% and 100% of full load capacity of the generator. As the combustion in diesel engines occurs by diffuse flame, the combustion occurs at stoichiometric condition. The values adopted for the fuel Lower Heating Value were 38,085 kJ/kg for the VO and 120,043 kJ/kg for the H_2. At first, the simulation occurred only with vegetable oil *in natura* (VO100) as fuel being kept constant its inlet mass flow rate at 1.558 g/s that means genset operating at its full load. After that, the addition of H_2 at the entrance of the intake manifold through an injector was simulated.

Similar to [14], this simulation varied the H_2 concentration from zero to 20% with steps of 5%. This implies VO reduction of the same amount (in energy basis). As a Lower Heating Value of H_2 is greater than the one for VO, the amount of VO energy replaced for H_2 was the

Table 4.
Data validation of the computational model with the experimental work of [13].

Parameters	Value of [13]	Simulation value	Diference (%)
Electric Power (kW)	14.82	14.79	0.002
Electric Performance (%)	24.95	24.92	0.001
Mass flow (g/s)	1.5589	1.5588	0.00

Source: The authors.

Table 5.
Variation of H_2 injection replacing the vegetable oil with the load.

Variation of VO and H2 ($x10^{-2}$ g/s)	Load					
	75%		80%		100%	
	VO	H2	VO	H2	VO	H2
VO100	116.9	0.0	124.7	0.0	155.8	0.0
VO95H5	115.1	1.8	122.8	1.9	153.4	2.4
VO90H10	113.2	3.7	120.8	3.9	150.9	4.9
VO85H15	111.4	5.5	118.8	5.9	148.4	7.4
VO80H20	109.5	7.4	116.8	7.9	145.9	9.9

Source: The authors.

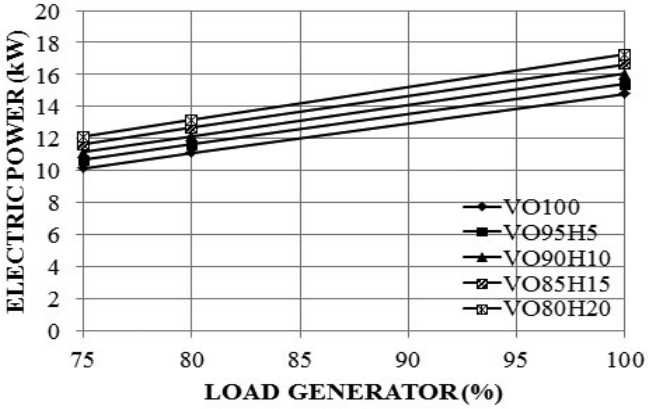

Figure 2. Variation of power with load for the addition of H2 in vegetable oil. Source: The authors.

same, but the amount of mass of H_2 that replaced the mass of VO was obviously smaller for each of the simulated cases, as shown in Table 5. The notation adopted for each amount of H_2 injected replacing VO were VO95H5 (5% H_2), VO90H10 (10% H_2), VO85H15 (15% H_2) and VO80H20 (20% H_2).

3. results and Discussion

Fig. 2 shows variations of the genset output electric power varying the generator load and H_2/VO ratio. The simulation showed that there was a linear increase in electrical power provided by the generator, when the H_2 content was increased. The output increased 16% at 75% of the nominal load and 14% at full load.

Fig. 3 shows the variation of brake specific fuel consumption (BSFC) with the generator load and H_2 concentration. Increasing H_2 content, BSFC decreased by 14.2% for operation for full load and decreased by 16.1% with the genset operating with 75% of the generator nominal load. The simulation suggested that the lowest value for the BSFC occurs when the genset run with 20% of H_2 and full load. In this case, the specific consumption is 309.13 g/kWh.

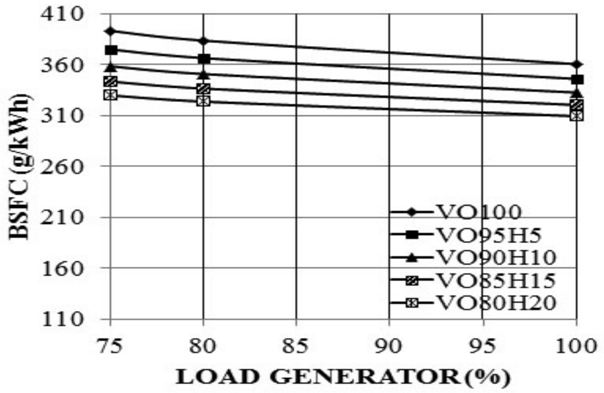

Figure 3. Variation of break specific fuel consumption with load for different H_2 content in vegetable oil.
Source: The authors.

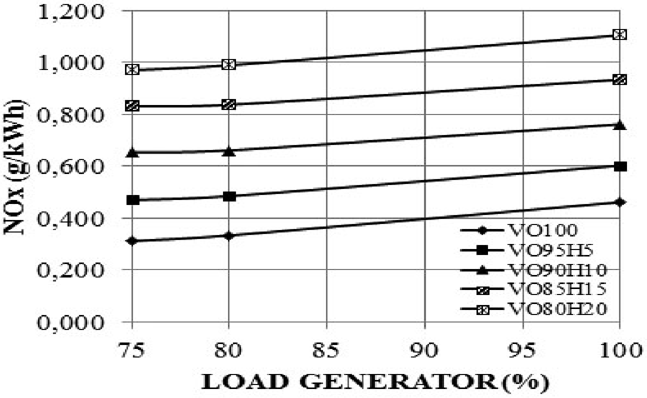

Figure 4. Variation of NO_x with load for the addition of H_2 in vegetable oil. Source: The authors.

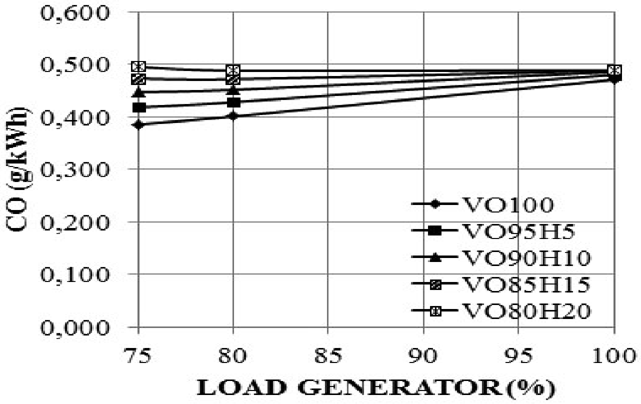

Figure 5. Variation of CO with load for the addition of H2 in vegetable oil. Source: The authors.

Fig. 4 shows NO_x concentration in the eluded gases changing the generator load for a different H_2/VO ratio. As expected, there was a significant increase in NO_x concentration with increasing H_2/VO ratio. At full load and 20% H_2, the NO_x concentration increased 58%. Running under full load and 20% of H_2, genset electric power increased from 14.8kW to 17.2kW. This is a consequence of replacing the vegetable oil-air mixture causing a reduction in the amount of air and, therefore, on the amount of N_2 raising the mixture's adiabatic flame temperature. As the Zeldovich mechanism is very sensitive to the reactant temperature, the rate of NO_x production increases exponentially with gas elevation. As the combustion chamber has excess oxygen and plenty of nitrogen, it results in a greater concentration of NO_x on the exhaustion gases in the case of H_2 doping.

Fig. 5 shows the variation of CO concentration varying the generator load and H_2/VO ratio.

Increasing H_2 content raised the CO concentration in exhaust gas by 28.3% when operating at 75% of the nominal load. However, if the H_2 content is 20%, the CO concentration stays almost constant independently of the generator load. This fact is very positive, mainly for genset operating in off-grid conditions and required to follow the load. In this case, doping the inlet air with 20% of H_2 will

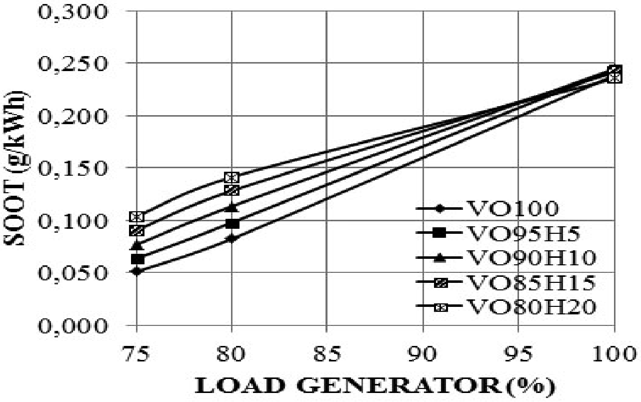

Figure 6. Variation of soot production with load for the addition of H_2 in vegetable oil.
Source: The authors.

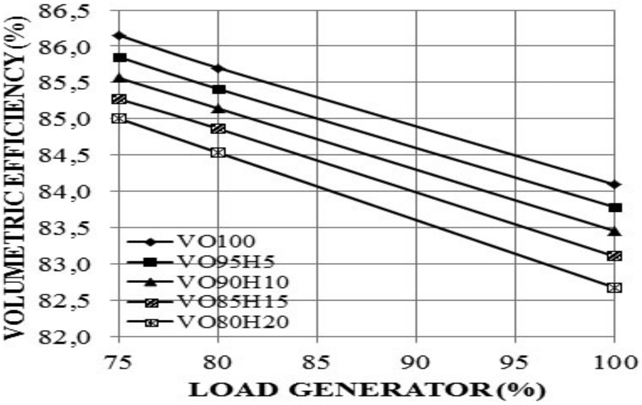

Figure 7. Variation of volumetric efficiency versus load and H_2 content in vegetable oil.
Source: The authors.

cause the CO concentration in the exhaustion gases to be kept constant and independent of the fuel flow rate.

Fig. 6 shows how soot formation varies with the generator load and H_2/VO ratio. Raising the load increases soot concentration. At 75% of the nominal load, the amount of soot doubles if the H_2 varies from 0 to 20%. On the other hand, at full load the amount of soot produced was almost constant and nearby 0.24 g/kWh. The minimum amounts of soot obtained was for VO100 and reached 0.051 g/kWh. Hydrogen competes for oxygen with carbon. At high load, much more carbon is injected for the same available amount of oxygen, therefore more soot is formed. At 75% load, the competition between carbon and hydrogen is more visible. Once more hydrogen is added, there is an oxygen shortage that promotes soot formation. Fig. 7 shows the volumetric efficiency versus load and H_2/VO ratio.

Increasing the generator load and H_2 content, the simulation showed a decrease in engine volumetric efficiency of 1.4% at generator load of 75% of the nominal load, and 1.7% when operating at full load. The simulation showed that for full load and 20% in H_2 content, volumetric efficiency can fall to 82.6%. This can happen because larger loads will require higher power (Fig. 2), which will increase the average temperature in the combustion chamber and increase the engine wall temperature. Then, engine walls will transfer heat to air in the intake system, reducing the air density, thereby reducing volumetric efficiency.

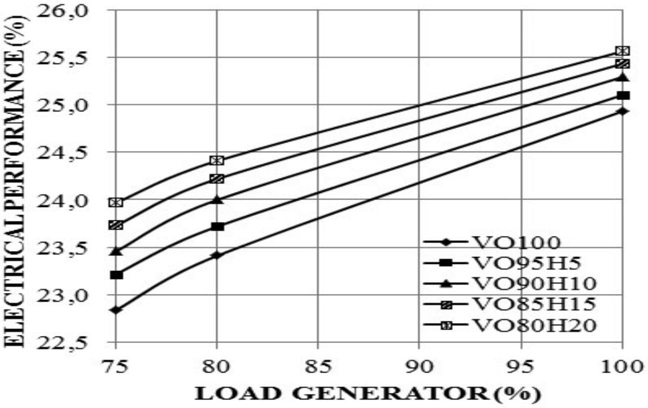

Figure 8. Variation of the genset electrical efficiency with load and H_2/VO ratio.
Source: The authors.

Fig. 8 shows the genset electrical performance versus load and H_2/VO ratio.

At the lowest load, there was a gain of nearly 5% in performance, and a 2.5% gain operating at full load. The simulation showed that the generator can reach values above 25.5% in performance with 20% H_2 in vegetable oil.

4. conclusions

The results showed significant improvements in the genset electric power and a decrease in brake specific fuel consumption with increasing hydrogen doping. The overall genset electrical efficiency improved as the hydrogen concentration was raised. The CO production remained constant with the maximum amount of simulated hydrogen for demanded medium and high loads on equipment. The values of NO_x and volumetric efficiency show the best levels with the use of vegetable oil *in nature* than with the introduction of hydrogen, while soot formation was increased but remained at a level close to 0.24 g/kWh, for any amount of tested hydrogen concentration when the genset operates at 100% load. The simulation showed that with the generator operating at medium load (75%), good results were achieved for the brake specific fuel consumption, which remained close to 329 g/kWh. The electrical efficiency of the genset at 75% load was 24%, close to the operation at full load, which was 25.5%. The general conclusion obtained from this simulation is that using hydrogen doping promotes a faster combustion of palm oil, improving its performance and CO emissions remain constant. These findings deserve to be investigated experimentally in gensets operating at medium loads or high loads, especially in regions with complex and expensive logistics, from the point of view of petroleum based fuels supply, such as the Amazon region.

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