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APPLICATION OF OPTIMIZATION TECHNIQUES TO PREDICTION OF PARAMETERS WIEBE FUNCTION IN A DIESEL GENERATOR SET

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Abstract. *The combustion in diesel engines involves complex physical and chemical process. One way to analyze it is through measuring the cylinder pressure during the complete combustion cycle. Once this pressure is known, it is possible to define parameters to evaluate the combustion process, engine performance, formation of pollutants, among others. However, due to its complexity, it is not possible to monitor this pressure in each diesel generator set, making it indispensable to use computational simulation tools to enable it. This study investigates the use of three optimization methods to predict the parameters of Wiebe function to estimate the pressure in the engine cylinder of a diesel generator set, using easily accessible parameters such as electric power and specific fuel consumption. To predict the parameters of Wiebe two computational programs were used, the AVL boost and the AVL design Explorer. The thermodynamic model of the engine was created using the AVL-boost and the optimization methods implemented with the AVL Design Explorer program. For the verification of the numerical results, the pressure curve obtained from a pressure sensor installed inside the first engine cylinder. The diesel generator set operated with a mixture of 8% biodiesel in diesel (B8) and 70% of the maximum nominal power. With the results obtained, it was verified that the parameters found of the Wiebe function. They were able to converge to their goal and predict the gas pressure inside the cylinder.*

Keywords: *Diesel generator set, Prediction, Optimization, Wiebe function.*

1. INTRODUCTION

The gradual increase consumption of fossil fuels, such as conventional diesel, motivates different researchers to find more suitable alternatives for their possible substitution or reduction in consumption. This fuel is widely used in compression ignition engines mainly in transportation, power generation and agricultural machinery. During time, due to the gradual increase of its price and to the incentive of several government agencies of different countries, different alternative fuels have been tested, such as ethanol, biodiesel, vegetable oils, hydrogen, among others (Agarwal, 2007; Hairuddin *et al.*, 2014; Prashant *et al.*, 2016). Lately, one of the most used to reduce diesel consumption is biodiesel, as is the case in Brazil, where the National Program for the Production and Use of Biodiesel (PNPB) introduced the use of this fuel in the national energy matrix in a mandatory way of 2% of biodiesel to diesel oil (B2) in 2008, increasing to 5% (B5) in January 2010, 7% (B7) in November 2014 and currently 8% (B8) (Anp, 2018).

Biodiesel is composed of alkyl esters of long chain fatty acids, usually produced from vegetable oils or animal fats by the transesterification process (Leung *et al.*, 2010). This alternative fuel is being used in several countries because it has properties that are relatively like diesel oil and can be used in most diesel engines without making any significant engine modifications (Hoekman *et al.*, 2012; Datta and Mandal, 2016). Its reported advantages include generally lower emissions of carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) compared to conventional diesel oil (Raheman and Phadatare, 2004; Rakopoulos *et al.*, 2006; Gumus and Kasifoglu, 2010; Behçet, 2011; Datta and Mandal, 2016). On the other hand, its viscosity improves the lubrication capacity of the engine and can extend the engine life (Hoekman *et al.*, 2012; Lanjekar and Deshmukh, 2016).

However, biodiesel has some limitations that need to be addressed since some of its properties affect engine performance, such as its lower calorific value and higher viscosity, which lead to less favorable conditions for complete combustion, reducing the thermal efficiency of the engine and consequently reflecting an increase in fuel consumption (Datta and Mandal, 2016). The problem of increasing specific fuel consumption is more evident in countries where the use of biodiesel mixed with diesel is mandatory, as in the case of Brazil, where both the transportation sector and the generation of electric energy felt the repercussions of the use of biodiesel blends in diesel engines (Anp, 2016). To make better this condition, it is necessary to modify or change the operating parameters of the engine, to improve the combustion process, reflecting the increase in thermal efficiency.

The combustion in diesel engines involves complex physical and chemical process. One way to analyze it is through measuring the cylinder pressure during the complete combustion cycle. Once this pressure is known, it is possible to define parameters to evaluate the combustion process, engine performance, formation of pollutants, among others. (Ghojel, 2010).

This technique could be applied to diesel generator sets operating in thermoelectric plants, allowing the adjustment of the engine's operational parameters to achieve better efficiencies for each type of fuel used. However, due to its complexity, it is not possible to monitor this pressure in each diesel generator set, making it indispensable to use computational simulation tools to predict this pressure, in combination with experimentally determined parameters. One of the most widely used models, although very simple, derives from the First Law of Thermodynamics and the equations of state of the ideal gases, considering the burnt and unburnt gases as an ideal homogeneous gas with uniform temperature and pressure, this model is usually called of zero-dimensional model (Colaço *et al.*, 2010b; a).

The zero-dimensional model does not include submodels to describe the chemical kinetics of the reactions involved in the combustion process, so they depend on some empirical or semi-empirical correlation to determine the rate of heat released by the fuel (ROHR) and with it thereafter the cylinder pressure. The most commonly used correlation is the Wiebe function, also known as Vibe, which relates four parameters: the start of combustion (SOC), the duration of combustion (CD) and the form parameter (m) and combustion efficiency (a) (Merker *et al.*, 2012). Although all models are very simple and easy to use, it has been shown that the Wiebe function parameters are specific to each engine and operating condition and can vary drastically as a function of load and fuel changes. For this reason, it is not possible to keep the parameters constant to try predict behavior with changes of load and fuel changes, since this implies that the mass fraction of the fuel burned (MFB) will be the same in all conditions analyzed, only if changes are obtained in the rate of heat release due to the increase or decrease in mass and the lower calorific power of the fuel (Iliev, 2014). Once the Wiebe parameters Wiebe function have been determined, it is possible to obtain the gas cylinder pressure and then understand the behavior of the motor and which combination of values generates the best performance. Thus, the determination of these parameters can be done from experimental results. However, this requires a lot of testing and calculations, making it impractical. Otherwise, optimization methods are tools that allow solving this problem in a more systematic and non-subjective way, even if they still use the experimental results.

The main objectives of applying optimization methods in internal combustion engines are to improve performance and reduce pollutant gases. These methods began to be more accepted because they are reliable and facilitate the work of the engineers in the phases of experimentation and computational simulation. Optimization is a systematic process used to find an optimal value of a parameter to be analyzed, when the possible configurations are infinite. This process is accomplished through numerical algorithms that explore the best search paths, according to uncertainty intervals and errors that are minimized at each iteration. In this sense, the optimization develops a safe work for the improvement of projects, which is independent of the operator (Shi *et al.*, 2011).

The optimization method uses objective functions that associate a number with infinite combinations of parameters (or variables). This number represents the maximization or minimization of the functions obtained by the modeling of the studied system. The optimal solution is one that has the highest or the lowest value within a global or local range. The purpose of this work is to determine, using three optimization methods, the appropriate parameters of the Wiebe function that allow to predict the optimum pressure inside the motor cylinder, from the parameters easily obtained, as is the case of electric power and specific fuel consumption. Two computational programs were used: AVL BOOST and AVL Design Explorer.

2. MATERIALS AND METHODS

2.1 Experimental Setup

The diesel generator set used in this work was the CUMMIS 4BT3.9 which features a four-cylinder engine with turbocharger and direct fuel injection. The main specifications of the diesel generator set are shown in Table 1. The generator was connected to a resistor bank that is used to vary the electric load, the electric power generated (Pe) was measured using the SAGA 4500 digital energy meter, already the volumetric flow rate of the fuel consumed by the engine was obtained using the FLOWPET-45 volumetric flow meter.

Table 1. Technical specification for diesel generator set.

Diesel generator set	
Marca	CUMMINS
Model	4BT3.9
Air intake	Turbocharger
Fuel injection	Direct
Number of cylinders	4
Diameter of cylinder [mm]	102
Piston stroke [mm]	120
Length of connecting rod [mm]	192
Compression ratio [-]	16,5:1
Rated speed [rpm]	1800
Rated maximum power [kW]	42
Alternator	
Electrical frequency [Hz]	60
Polarity	4 polos
Number of phases	3
Output voltage [V]	220/380
Power factor [-]	0,8

Knowing the volumetric flow consumed by the engine and the fuel temperature, its density was determined and laterally the mass flow. At the same time, K-type thermocouples were used to measure the temperature of the gases at the beginning of the exhaust manifold outlet, as close as possible to the first cylinder.

The internal pressure in the cylinder was measured using the pressure data acquisition system model AVL Indimicro 602, together with a piezoelectric sensor model AVL GU21D installed inside the cylinder, with a measuring capacity of up to 250 bar. The rotation sensor model AVL 365C has been installed on the crankshaft axis for the measurement of the engine speed and its synchronization with the cylinder pressure in real time. The schematic view of the experimental setup is shown in Fig. 1.

Three different loads of 50, 70 and 100% of the rated maximum power were applied and compared. The data were obtained with the engine operating in steady state and, as a parameter to demonstrate that it reached this state, the exhaust gas temperature (T_{gas}) was chosen. To guarantee the reliability of the results, three tests were repeated for each load tested and the result corresponds to the average of the tests performed.

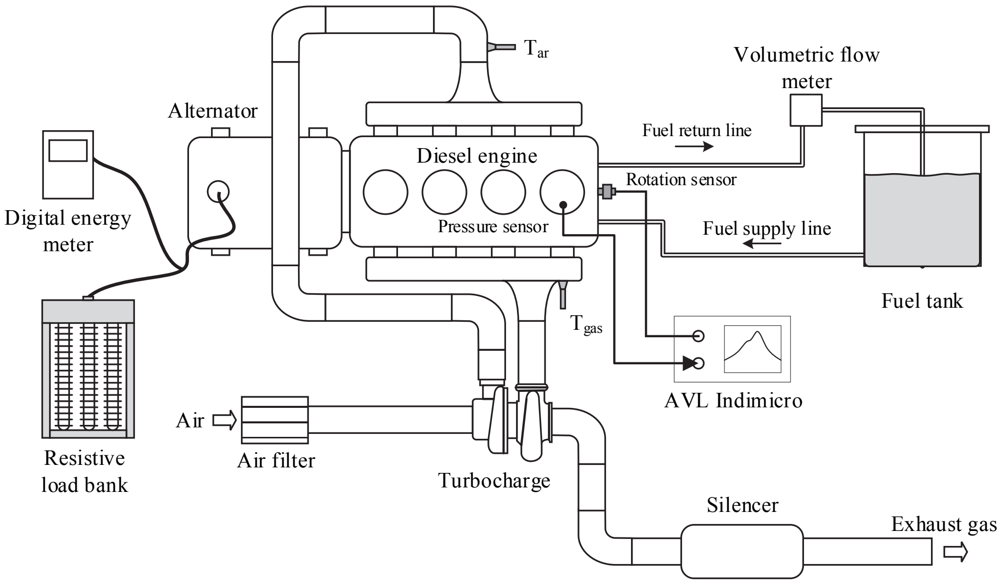

Figure 1. Schematic view of the experimental setup

2.2 Model Formulation

Numerical simulation is a fundamental part of development process of the internal combustion engines. One program currently used for several researchers is the simulation program AVL-BOOST (Lešnik *et al.*, 2014; Nikzadfar and Shamekhi, 2014; Rimkus *et al.*, 2015), created for thermodynamics applications and developed exclusively to modeling internal combustion engine. The program consisting mainly in two combustion models, zero dimensional and one-dimensional, which are based on the First Law of Thermodynamics for control volume.

The models frequently used in AVL-BOOST for diesel engines are the two zones Wiebe model and AVLMCC model (controlled mix combustion). For this work was chose the two zones Wiebe model, where the main component of this model is the mass fraction burned (MFB) as a function of the advance of crank angle (θ), which is obtained through Wiebe function (Merker *et al.*, 2012), this empirical function expresses the mass fraction burned as a exponential function involving start of combustion (*SOC*), combustion duration (*CD*), shape parameter (*m*) and parameter (*a*), as shown in Eq. 1.

$$MFB = 1 - \exp\left[-a\left(\frac{\theta - SOC}{CD}\right)^{m+1}\right] \tag{1}$$

Using the Wiebe function defined by Eq. 1 it is determined the rate of heat release of fuel (*ROHR*), as shown in Eq. 2, as a function of the lower calorific value of the fuel (PCI_{comb}) and the mass of the fuel in the combustion chamber per cycle (m_{comb}).

$$ROHR = m_{comb} PCI_{comb}\, a\,(m+1)\left(\frac{\theta - SOC}{CD}\right)^{m} \exp\left[-a\left(\frac{\theta - SOC}{CD}\right)^{m+1}\right] \tag{2}$$

Know de ROHR it is possible to determine the pressure inside de cylinder, but for this initially the parameters of the Wiebe function must be defined. One way to determine the Wiebe parameters is to use optimization methods (Verma and Lakshminiarayanan, 2006), with them it is possible to solve the inverse problem, which in this article approaches the estimation of the effective power and specific consumption of the fuel related to those obtained experimentally. In this way the objective function was defined as the minimization of the global error (ε_{obj}). Determined for both parameters as shown in Eq. 3.

$$\varepsilon_{obj} = \frac{Abs\left|P_{e,\exp} - P_{e,simu}\right|}{P_{e,\exp}} + \frac{Abs\left|Cesp_{\exp} - Cesp_{simu}\right|}{Cesp_{\exp}} \tag{3}$$

Where $P_{e,exp}$ e $P_{e,sim}$ are the effective power determined experimentally and simulated in kW, since $Cesp_{exp}$ e $Cesp_{simu}$ are the specific fuel consumption of experimental and simulated fuel in g/kW-h.

For the implementation of the optimization methods, the Design Explorer program was used, and it is necessary to define the variables and the objectives to be achieved. To reduce computational time, the value of 6.908 for the parameter representing an energy conversion of 99.9% was attributed to various bibliographical references (Gupta, 2013; Ferrari, 2014; Iliev, 2014; Caton, 2016).

As previously mentioned, considering the known parameter a in this work, three variables to be determined are the unknown parameters of the Wiebe function, the start of combustion (SOC), the duration of the combustion (CD) and the parameter of form m. The range of variation of each parameter was previously defined to achieve the overall objective that best represents the reality of the engine operation.

For the case of the start of combustion, the variation range was determined as a function of the minimum and probable maximum delay. In this work a minimum combustion delay of 0.5 ms and a maximum delay of 1.0 ms were defined as a function of the values presented by Mollenhauer andTschoeke (2010) e Heywood (1988). Considering that the engine runs at a constant speed of 1800 rpm and fuel is injected 13 ° before the upper dead center, the range of the start of combustion of -7.7 ° ≤ SOC ≤ -2.4 ° has been determined. The CD parameters in the variation ranges were determined according to the maximum and minimum values recommended in the program manual (Avl-Boost, 2014), obtaining the following values 55 ° ≤ CD ≤ 90 ° and 0,2≤ m ≤ 1.1.

The initial values of m, SOC and CD were 0.65, -5.6 ° and 72.5 ° respectively, both determined as a function of the arithmetic mean of the values maximum and minimum parameters.

To compare the numerically determined Wiebe parameters, the experimental results of the pressure curve were used to determine the burned fuel mass and later to perform a curve fit by the Levenberg-Marquardt method (Hu *et al.*, 2018), thus obtaining the representative Wiebe parameters in function of the experimental results.

2.3 Optimization Methods

2.3.1. Genetic Algorithm (GA)

The genetic algorithm method was inspired by Darwin's theory of evolution as a function of the analysis of the natural process of evolution in biological populations, in which individuals more adapted to a medium tend to survive in it and perpetuate the genetic information stored in the chromosomes evolving through convergence towards an ideal individual. The method starts from an initial population, to later form a new set of evolved individuals (possible solutions), the result of several crosses and mutations along the iterations. The process repeats itself until it reaches the desired objective, finding optimal solutions (being local or global) reaching the point where the individuals can no longer obtain another solution with better values, thus identifying the possible global minimums or maximums (Garcia and Tasinaffo, 2008; Zhu *et al.*, 2015)

2.3.2. NLPQL

NLPQL was developed using quadratic approximation of the Lagrange matrix with Karush-Kuhn-Tucker (KKT) conditions and can be solved using the Newton Raphson method. This method of optimization generates a sequence of quadratic programming subproblems that must be solved successively, the method is therefore known as the Sequential quadratic programming method (SQP) and assumes that objective functions and constraints are continuously differentiable (Hu *et al.*, 2017).

Usually, this method is very efficient to solve optimization problems of maximum or minimum locations. The major disadvantage of NLPQL is that it is a deterministic method and requires a starting point close to the goal to reach the desired value (Chen and Lv, 2014).

2.3.3. Nelder Mead

This simplex method is perfected by Nelder and Mead in 1965. It is a deterministic direct search method, which starts from an initial simplex set of random points and with each new iteration a new simplex is constructed (Gonçalvez, 2013). These points, called vertices are updated at each iteration until reaching the optimal value of the objective function; the vertices are organized according to the coefficients of expansion, deflection, reduction and contraction.

The advantages of this method are: independence of the function differentiability, few evaluations of the objective function, agile solution. The objective function, however, must be continuous.

3. RESULTS AND DISCUSSIONS

In this item, we present the experimental and numerical results obtained as a function of the procedures described in item 2. Fig. 2 shows the mass fraction of burned fuel (MFB) obtained experimentally, together with the Wiebe parameters determined by the curve adjustment by Levenberg- Marquardt. The regression coefficient of the adjustment was 0.9941, showing a good representation of the MFB experimental curve. The start of combustion was -5.00 °; the value of 67.73 ° for the duration of the combustion and the m parameter of the Wiebe function of 0.33.

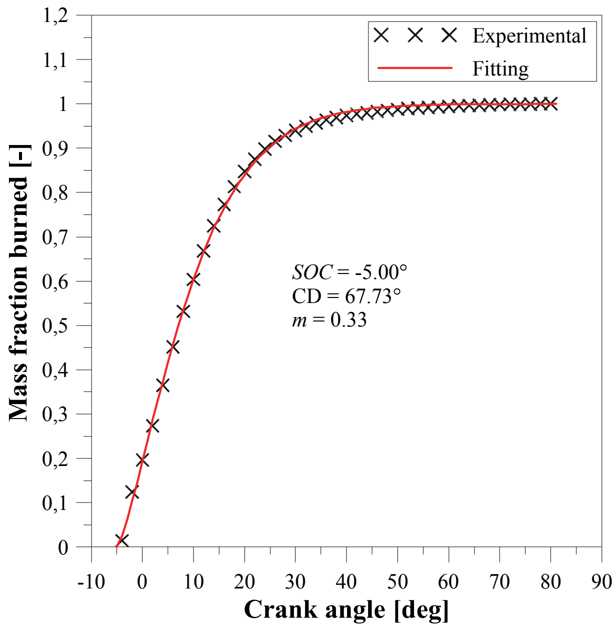

Figure 2. Mass fraction burned versus crank angle

Figure 3 illustrates the convergence of the GA optimization method when the experimental values of 9.03 kW effective power and 173.33 g/kW-h specific fuel consumption of are defined as objectives to goal. After 100 generations with a population of 50 individuals it was verified that there are several variations of Wiebe parameters (SOC, CD and m) that meet the established objectives, as shown in Fig. 3(a). Where each sphere represents an individual and the size of them the global error of the objective determined in function of Eq. 3.

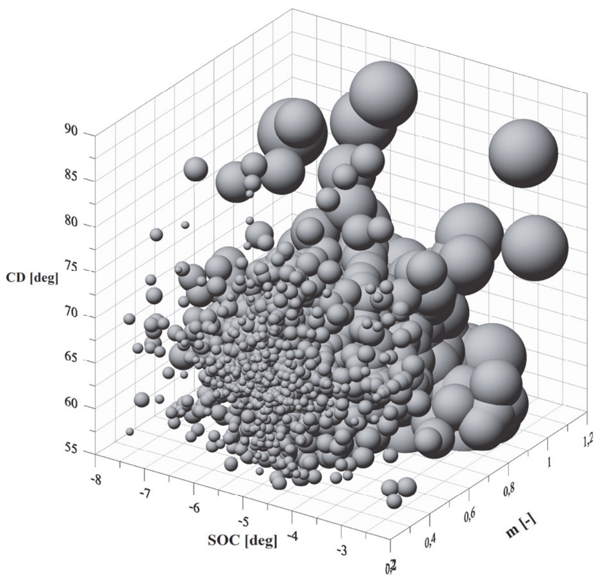

Figure 3 (a). Convergence of genetic algorithm

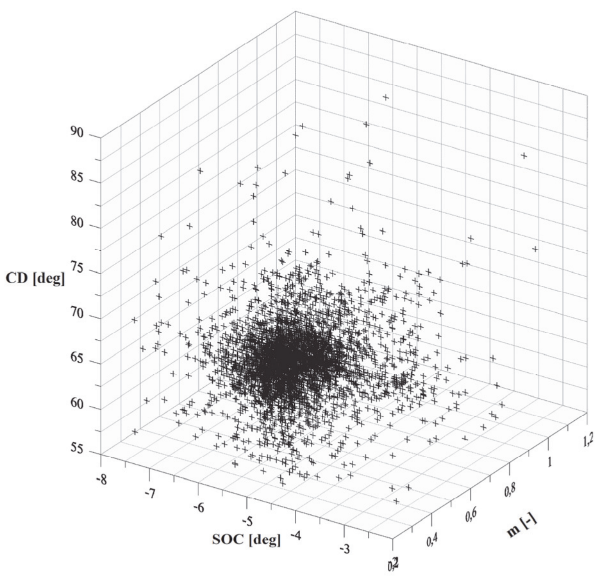

Figure 3 (b). Convergence of genetic algorithm

Fig. 3(a) shows a large concentration of the smaller spheres (less error) in a specific region, which can be better appreciated in Fig. 3(b), showing that even obtaining low errors at different locations than most of the iterations with the smallest error are concentrated in a specific region, where the average of the points of this region was considered as the result of the optimization the average of the last thousand iterations that obtained the smallest global error.

The results obtained by the Nelder-Mead method are shown in Fig (4), the parameters determined with this method had percentage increases of 14.15 and 20.94% for the start of combustion and parameter m, respectively. However, the duration of the combustion had a reduction of 3.52%. It was also evidenced a maximum pressure peak with an increase of 3.06% in relation to the experimental result.

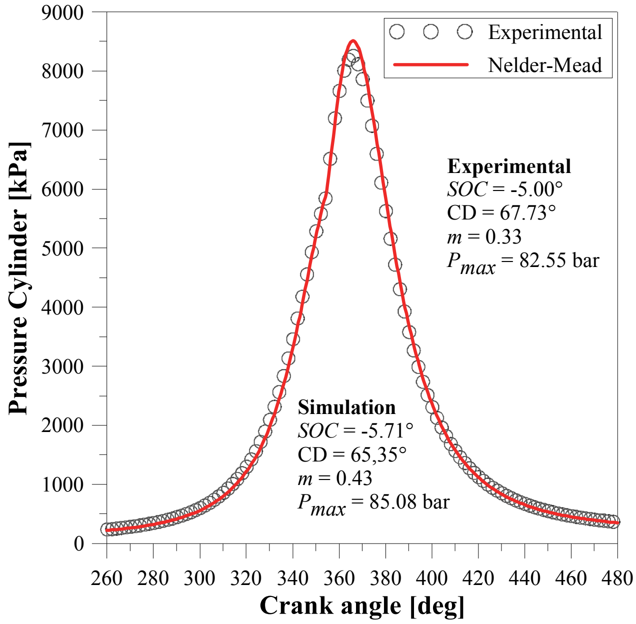

Figure 4. Cylinder gas pressure related to crank angle with Nelder-Mead method

For the NLPQL method the results are shown in Fig (5), the parameters defined from this method have obtained percentage increases of 14.15 and 15.18% for the start of combustion and parameter m, respectively. However, the duration of combustion decreased by 3.51%. Also, a maximum pressure peak was observed with a 3.80% increase in relation to the experimental result. Similar values were obtained with the Nelder-Mead method.

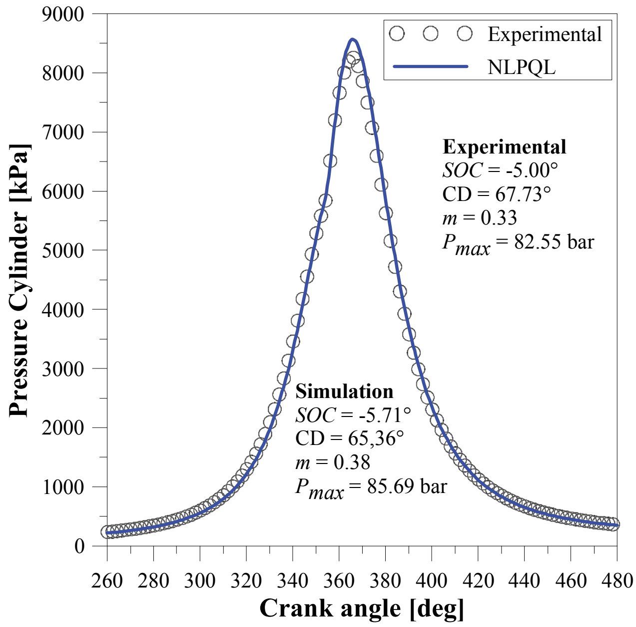

Figure 5. Cylinder gas pressure related to crank angle with NLPQL method

For the GA method, the results are shown in Fig (6), the parameters established with this method presented some percentage reductions of 0.87, 15.95 and 2.08% for the start of combustion, parameter m and duration of combustion, respectively. Regarding the experimental result, a maximum pressure peak with an increase of 5.51% was evidenced.

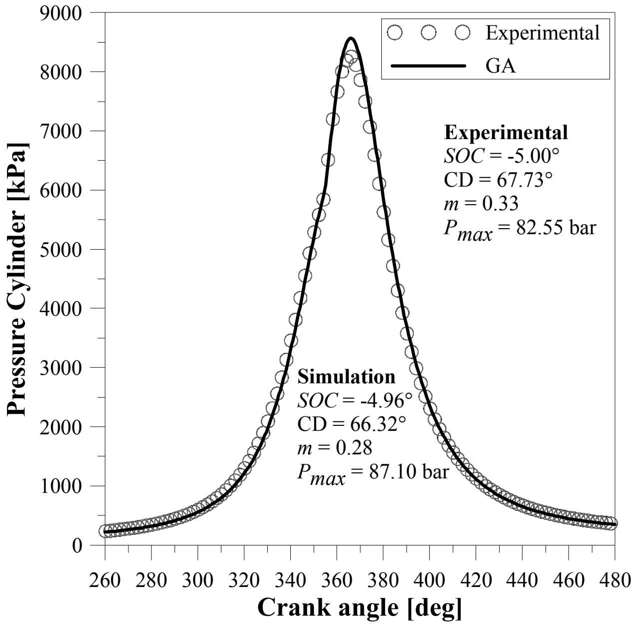

Figure 6. Cylinder gas pressure related to crank angle with GA method

4. CONCLUSIONS

In the proposed study we analyzed the capacity of using three optimization methods to determine the unknown parameters of the Wiebe function and consequently to predict the pressure inside the cylinder. The results showed that the chosen optimization techniques can be used to determine the combustion parameters if the objective function is correctly defined.

However, to obtain good results with the deterministic methods (Nelder-Mead and NLPQL) it is necessary that the ranges of variation of each parameter are close to the desired goal. Otherwise, the methods may encounter local or global minimums that do not represent the actual operating condition desired.

Analyzing the results established from the methods used, it is observed that although all provided low overall errors of 0.05, 0.07 and 0.01% with the Nelder-Mead, NLPQL and GA methods, respectively, the genetic algorithm achieved results closer to the experimental, which was already expected if it was a heuristic method. However, in comparison to deterministic the time of convergence of this method becomes high, as well as its computational cost. Therefore, we have as an alternative the creation of a hybrid method, combining the desired characteristics of deterministic and heuristic methods aiming the improvement of the optimization processes.

Analyzing all the results, it can be concluded that it is possible to predict the behavior of the diesel generator set as a function of the measurement of the electric power and specific fuel consumption corroborated with optimization methods for the determination of the unknown parameters of the Wiebe function, in the same way as it was verified by Colaço *et al.* (2010b).

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