

Mathematical modeling of the working temperatures of a diesel engine coupled to a generator and powered by a diesel-Jatropha oil blend

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Resumen

En este trabajo, se desarrollaron modelos matemáticos para correlacionar las temperaturas de trabajo de un motor diesel con la carga y el contenido de aceite de Jatropha curcas en combustible diesel. Se utilizó un motor de inyección indirecta Lister Petter y una mezcla de diesel con 5 y 10% de aceite de Jatropha. Se utilizó un Diseño Factorial para planificar los experimentos y la Metodología de Superficie de Respuesta (RSM) para desarrollar las correlaciones. Los modelos obtenidos se utilizan para predecir las temperaturas de los gases de escape de los cilindros y las temperaturas del refrigerante en la entrada y salida del radiador. El contenido de aceite en el combustible no provocó cambios significativos en las temperaturas de los gases de escape o del refrigerante. La mezcla diésel con aceite vegetal de Jatropha al 10% no produce cambios en el comportamiento térmico del motor, por lo si se considera solo este comportamiento, la mezcla se podría emplear directamente en este tipo de motores sin realizar modificaciones.

Palabras clave: motor diesel, Jatropha, aceite vegetal, modelación matemática

Abstract

In this work, mathematical models to correlate the working temperatures of a diesel engine with the load and the oil content of Jatropha in diesel were developed. A Lister Petter indirect injection engine was used and a blend of diesel fuel with 5 and 10% of Jatropha oil. A Factorial Design was used to plan the experiments and the Response Surface Methodology (RSM) in order to develop the correlations. The obtained models may be used to predict the exhaust gases temperatures and the coolant temperatures at the inlet and outlet of the radiator. The Jatropha oil content in the fuel did not cause significant changes in the exhaust gas or coolant temperatures. The diesel blend with 10% of Jatropha oil does not produce changes in the thermal behavior of the engine, so just taking into account this single approach, blends can be used in this type of engine without making any modifications.

Keywords: diesel engine, Jatropha, vegetable oil, mathematical modeling

1. Introduction

The energy consumption is continuously increasing with industrialization and with the growth of the world population [1]. The air pollution of the planet is a serious problem that grows considerably over the years and is strongly related to energy production. This pollution is caused by the use of fossil fuels in transportation and generation of electricity [2]. Internal combustion engines (ICE) are the most widely used equipment for these purposes. Diesel engines plays a dominant role in: heavy vehicles, agricultural machinery, engineering machinery, power production and other fields due to its high energy efficiency and good economic characteristics [3].

Manufacturers of ICE and scientists involved in this area of knowledge have been researching, designing and testing alternative technologies that provide sufficient power while remaining within regulatory gas emission limits [2]. Some of these new alternatives have been: the use of vegetable oils and their derivatives as fuels, the use of fuel emulsions, hydrogen, alcohol, nanoparticles and other additives [4-8].

The use of *Jatropha* oil as fuel has been widely investigated due to the potential of its blends with diesel fuel. In Cuba, several studies have been carried out that analyze the behavior of engines using this type of alternative fuels, as well as their physical-chemical properties [9-12]. These works highlight the feasibility of using *Jatropha* oil as fuel in diesel engines.

Experimental measurements on engine performance and emissions experimentally for the evaluation of new technologies is complex, time-consuming and expensive [2]. For the development of these researches, it is necessary to carry out many experiments, which is why in recent years there has been an increasing interest on the use of mathematical models to predict and optimize the behavior and emissions of ICE [13]. One of the most important advantages of mathematical modeling is that its application minimizes processing time and cost, by reducing the need to perform countless and complex experimental work [14]. A mathematical model is nothing but the representation which characterizes a physical system or process, which can be obtained in two ways: strictly theoretical (theoretical modeling) and experimentally, based on real input and output data from the system (experimental modeling). The main advantage of process modeling is that it allows predicting the dynamic and static behavior of systems before building them and analyzing the performance of an existing one in order to study its behavior. Furthermore, using modeling does not expose the process to damage and can determine what might happen to it by simulating the model with an unusual input condition or disturbance. These models have even been used for the prediction of some properties of fuels such as surface tension and cetane number, with very good results [15, 16].

When it comes to evaluating technologies and predicting the behavior of an ICE, the most important parameters have been: fuel consumption, exhaust emissions, efficiency, in-cylinder pressure, torque, effective power, ignition delay, among others. Various researchers have tried to predict these parameters and for this they have mainly used the response surface methodology [17].

Dhole et al. [18] presented mathematical models of some experimental research carried out for different combinations of gas and diesel under a wide range of load conditions for a turbocharged four-cylinder diesel engine. The response variables considered in this work were the brake thermal efficiency, the emissions of unburned hydrocarbons, carbon monoxide and nitrogen oxides. On the other hand, the use of mathematical models to predict the specific fuel consumption and exhaust gas emissions of a diesel engine as a function of the load and the volume of magnetic nanoparticles of Fe_3O_4 is reported [17]. Regression analysis was performed using the experimental data. The experiments were carried out with nanoparticle concentrations of 0.4 and 0.8% by volume. The

predicted values obtained by the regression equations were compared with those obtained from the experimental measurements. Regression adjusted models were able to predict specific fuel consumption and emission characteristics with a correlation coefficient R^2 in the range of 94-98%.

Several studies about the influence of the use of different types of biodiesel and vegetable oils on exhaust emissions and fuel consumption of diesel engines have been reported [7, 19, 20]. In addition to the gas emissions and fuel consumption of an ICE, heat transfer is an important requirement. In the analysis, development and design of the internal combustion engine, the temperatures of the system are directly related to its efficiency and to the pollution level that these engines generates [21]. However, there are few reports on the influence of the use of this type of fuel on the working temperatures of an engine.

From the point of view of mathematical modeling, temperature has been one of the least studied parameters for its prediction and optimization from experimental data. That is why the objective of this work is to obtain a mathematical model that allows predicting the working temperatures of an indirect injection diesel engine, depending on the load and the content of crude *Jatropha* oil blended with diesel fuel, through the response surface methodology.

2. Materials and Methods

Fuel properties

The fuels used were diesel fuel and crude *Jatropha* oil. For the tests carried out on the combustion engine, a diesel-oil blend of *Jatropha* oil at 5 and 10% was used. The main properties of these fuels and the methodology followed for the preparation of the blend can be found in [6].

Engine test bench

A Lister Petter LPWS2, two-cylinder, indirect injection diesel engine was used for the tests. The engine has a rigid connection coupled to an electric generator. The main characteristics of the engine and the generator are shown in Table 1. The load is applied by means of a system of electrical resistances that are connected to the generator. When they are turned on consuming energy, they cause the different loads in which the engine works. The engine load can vary from 0 to 96% in a range of 16% load.

Table 1. Technical specifications of the engine and generator

Engine		Generator	
Cylinder diameter (mm)	86	Maker	Lister Petter
Stroke (mm)	80	Model	BC1164D1
Displacement (L)	0.930	Power factor	0,86
Compression ratio	23.5:1	Tension (V)	220
Constant speed (rpm)	1500	Speed (rpm)	1500
Cooling type	Water	Frequency (Hz)	50

Another element of the experimental installation is the control panel, where most of the instruments that allow to control and measure the parameters of the generator set are located. The engine has a series of thermocouples installed that allow to follows the behavior of some of the main operating temperatures to be analyzed in real time. A diagram of the experimental installation with the location of the thermocouples and the analyzed temperatures is presented in Figure 1.

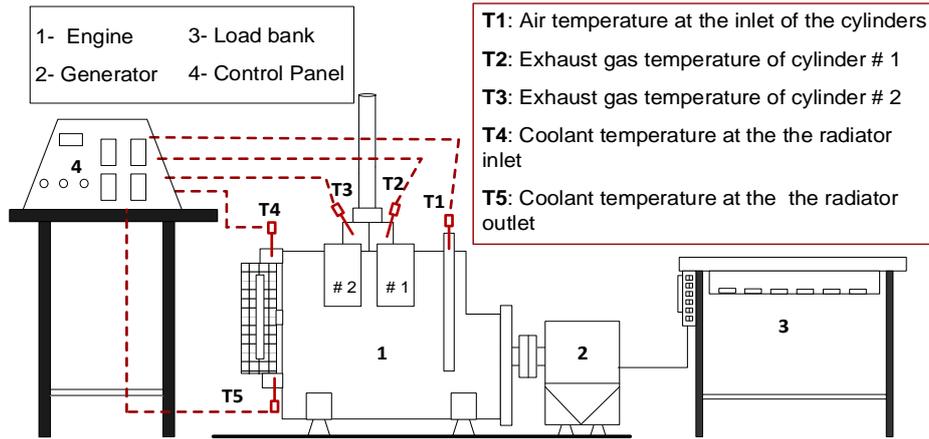


Fig.1 Scheme of the experimental installation used

For each experiment and to determine the working temperatures of the engine, the fuel feed system was initially cleaned and sweetened, to later fill the store tank with the fuel to be used in each run. Then the engine was started until it reached the optimum working temperature, coolant at the radiator outlet (T4 = 84°C) and it was settled (approximately five minutes) until the main engine parameters were stable. The humidity and the room temperature were kept in the range of 65-78% and 31-33°C, respectively. The electricity generator was then activated to start feeding the load bench. To begin providing the engine load, two resistors from the load bench were connected to the system and five minutes were set up until the stabilization of the engine parameters. Then, the temperature data was collected with the Control Panel. The load bench has 12 electric resistances that are connected in pairs so that six different loads are applied to the engine.

Experimental design

To carry out the experiments and for their subsequent analysis, a multilevel factorial design with two factors was used: the engine load (Load) and the crude oil content of Jatropha in the fuel (JCO). The levels selected for each factor were six and three respectively. The ranges and levels of the independent variables are shown in Table 2.

Table 2. Factors and their variation levels

Factors	Units	Levels					
Load	%	16	32	48	64	80	96
JCO	%	0		5		10	

According to the factorial design used, 6*3 = 18 experiments should be performed. Each experiment was repeated three times to ensure the repeatability of the results, and was performed randomly. T1 was kept at 32 ± 1°C. All the variables used are real, and are supported with experimental data. The response variables analyzed with RSM in the experimental design were:

- T2: Exhaust gas temperature of cylinder # 1 (°C).
- T3: Exhaust gas temperature of cylinder # 2 (°C).
- T4: Temperature of the cooling liquid at the radiator inlet (°C).
- T5: Temperature of the coolant at the outlet of the radiator or heat exchanger (°C).

The response surface methodology (RSM) is composed of a group of mathematical and statistical models in which the response of interest depends on different variables, and the objective of the method is to model and optimize this response. To achieve this goal, a linear or square polynomial equation is established to define the case study. In most of the publications that use RSM, the equations that relate the responses to the independent variables are not reported. That is why the first step to apply the RSM is to find an approximation function between the inputs and the outputs of the analyzed process [13]. In most cases, RSM uses a low-order polynomial as a mathematical model. When the relationship between the parameters is linear, the approximation function is a first-order model or polynomial (1). If the relationship between the parameters is not linear then it fits a second order polynomial (2).

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \varepsilon \quad (1)$$

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i_1 > j}^k \sum_j^k \beta_{ij} X_i X_j + \varepsilon \quad (2)$$

where Y is the response variable (T2, T3, T4 and T5), X_i and X_j are the independent variables (Load and JCO), i is the linear coefficient, j is the quadratic coefficient, β corresponds to the regression coefficients, k is the number of factors studied in the experiment and ε is a random experimental error, which is assumed to have a mean equal to zero [22].

The analysis of variance (ANOVA), Fisher's statistical test (F test) and p-value <0.5 (indicates that the parameter is significant with a 95% confidence level) were used to verify the statistical significance of the individual parameters in each response variable. To evaluate the fit of the models proposed by RSM, the statistical parameters Correlation coefficient (R^2), adjusted correlation coefficient (R^2_{adj}) and the mean absolute error (MAE) were used. Statistical analyzes and mathematical models were performed using the statistical program Statgraphics Centurion XV version 15.2.14 (StatPointTechnologies Inc.). The response surface graphs were performed with the MATLAB R2018a program version 9.4.0.813654 (MathWorks Inc.).

3. Results and Discussion

The RSM proposed a correlation of the response variables (in this case the working temperature of the engine) with the factors of the design used (JCO and Load). The second order polynomials (quadratic models) were the ones that better explained the variation and dependence of the variables because they had the best R^2 , R^2_{adj} and MAE fits. The mathematical models obtained for T2, T3, T4 and T5 are presented in Equations 3-6 respectively.

$$T2 = 148.625 + 1.129 \cdot \text{Load} + 0.302 \cdot \text{JCO} + 5.88 \cdot 10^{-3} \cdot \text{Load}^2 - 4.8 \cdot 10^{-3} \cdot \text{Load} \cdot \text{JCO} \quad (3)$$

$$T3 = 156.24 + 1.299 \cdot \text{Load} + 0.098 \cdot \text{JCO} + 4.742 \cdot 10^{-3} \cdot \text{Load}^2 - 2.995 \cdot 10^{-3} \cdot \text{Load} \cdot \text{JCO} \quad (4)$$

$$T4 = 83.898 + 0.019 \cdot \text{Load} - 0.011 \cdot \text{JCO} + 0.032 \cdot 10^{-3} \cdot \text{Load}^2 - 0.118 \cdot 10^{-3} \cdot \text{Load} \cdot \text{JCO} \quad (5)$$

$$T5 = 25.723 + 0.071 \cdot \text{Load} - 0.032 \cdot \text{JCO} - 0.194 \cdot 10^{-3} \cdot \text{Load}^2 - 0.866 \cdot 10^{-3} \cdot \text{Load} \cdot \text{JCO} \quad (6)$$

R^2 is an indicator that determines the fit of the experimental data with the model proposed by the use of RSM. It is preferred that the difference between R^2 and R^2_{adj} is less than 0.2. Low MAE values indicate the precision of the prediction techniques when comparing predicted versus observed values. The values of R^2 , R^2_{adj} and MAE obtained for each model are presented in Table 3.

Table 3. Statistical parameters of the models proposed by RSM

Models	Equation	R²	R²adj	MAE
T2	3	99.978	99.965	0.591
T3	4	99.982	99.972	0.539
T4	5	94.549	91.434	0.132
T5	6	98.993	98.418	0.123

The high values in the coefficients R^2 and R^2_{adj} , as well as the low MAE values of the obtained models reveal that the regression models describe the experimental data with high levels of reliability. The fit of the proposed quadratic models can also be assessed by the analysis of variance, which is based on the "F value" and the "P value". In general, the pattern of interactions between different parameters can be identified by considering the F value and the P value. It should be noted that the higher the F value and the lower the P value, the corresponding variables are more significant and important in the model [23]; a P value lower than 0.05 means that the analyzed factor is statistically significant on the response variable, with a confidence level of 95%. Table 4 shows the results of the analysis of variance of the response variables studied.

Table 4 Results of the analysis of variance

Source	T2		T3	
	F value	P value	F value	P value
Load	30934.30	0	38703.94	0
JCO	0.36	0.566	1.92	0.209
Load²	187.91	0	144.22	0
Load·JCO	5.74	0.051	2.63	0.149
Source	T4		T5	
	F value	P value	F value	P value
Load	118.87	0	609.63	0
JCO	2.33	0.171	66.73	0
Load²	0.13	0.726	6.29	0.041
Load·JCO	0.08	0.785	5.72	0.048

As Table 4 shows, some of the factors analyzed and their respective interactions are not statistically significant ($p > 0.05$) for engine temperatures. The linear factor of JCO and its interaction with Load have no statistical significance for T2. However, the quadratic term is significant in the behavior of T2 and in the mathematical model that describes it. In the case of T3, only the linear and quadratic terms of the Load factor are statistically significant for its mathematical model, not for the interaction of the parameters and for the JCO factor. For T4, the quadratic term, the interaction of the factors and the linear term of JCO are not statistically significant. Finally, all the terms, both linear, quadratic and the interaction of the factors are statistically significant for the mathematical model that represents the behavior of T5. When analyzing the F value, it can be seen that the term Load presents the highest values, being the most important input variable and the most influencing factor on the engine temperatures analyzed according to the RSM. By eliminating the terms that did not

have statistical significance from the previous mathematical models, the following correlations are obtained:

$$T2 = 148.625 + 1.129 \cdot \text{Load} + 5.88 \cdot 10^{-3} \cdot \text{Load}^2 \quad (7)$$

$$T3 = 156.24 + 1.299 \cdot \text{Load} + 4.742 \cdot 10^{-3} \cdot \text{Load}^2 \quad (8)$$

$$T4 = 83.898 + 0.019 \cdot \text{Load} \quad (9)$$

$$T5 = 25.723 + 0.071 \cdot \text{Load} - 0.032 \cdot \text{JCO} - 0.194 \cdot 10^{-3} \cdot \text{Load}^2 - 0.866 \cdot 10^{-3} \cdot \text{Load} \cdot \text{JCO} \quad (10)$$

The response surface graphs with the interactions between the independent variables (Load and JCO) and the different response variables (T2, T3, T4 and T5) are shown below in Figures 2-6. The effect that Load and JCO have on the exhaust gas temperatures of the engine cylinders is shown in Figures 2 and 3 respectively.

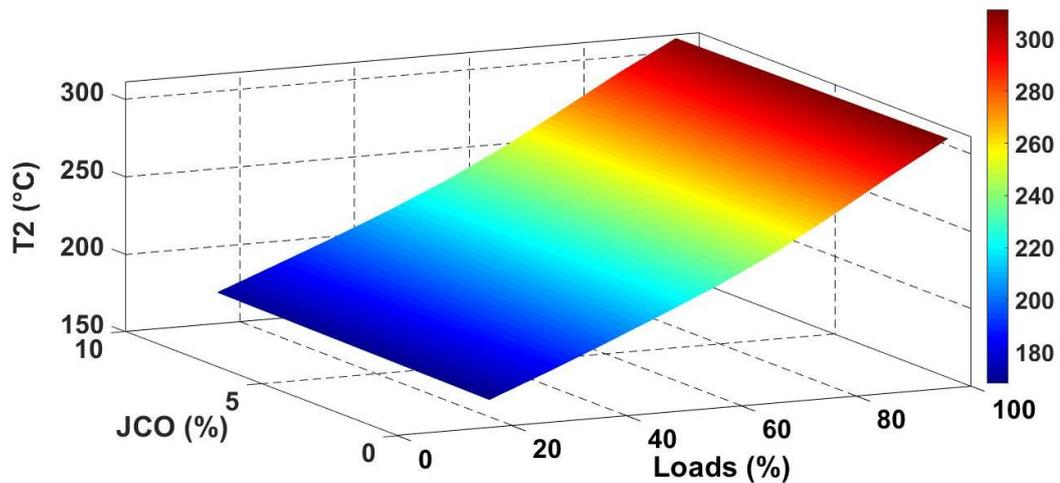


Fig.2 Response surface of T2 vs. Load and JCO

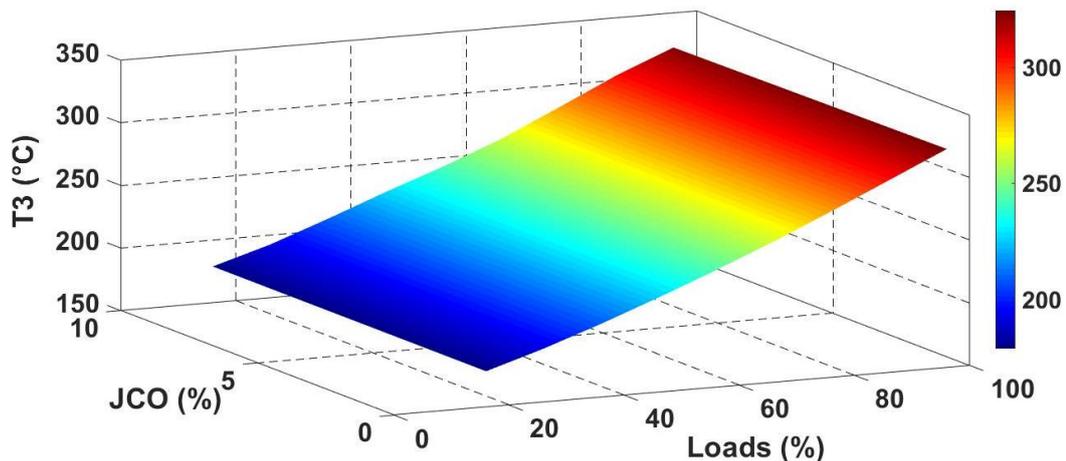


Fig.3 Response surface of T3 vs. Load and JCO

As can be seen in Figures 2 and 3, the increase in the engine load (Load) causes a significant increase of the exhaust gases temperatures from the engine cylinders (T2 and T3). This is because increasing the load, more fuel and air are into the combustion chamber to produce more power output. Under these conditions the turbulence of air inside the chamber is enhanced, therefore, a more homogeneous air-fuel blend inside the combustion chamber is obtained [24].

Furthermore, the fuel injection pressure increases with increasing engine load resulting in higher quality of the atomization process and smaller fuel droplets. As a result of the increase in air turbulence and the increase in the quality of the atomization process, the combustion quality is considerably increased [25]. That is why the highest values of T2 and T3 are obtained when the engine works at its maximum load. The combustion process that occurs in diesel engines with multiple cylinders does not occur under identical conditions in all combustion chambers, it is normal to see temperature differences of up to 20 °C [26]. However, the observed difference in cylinder temperatures may be related to the state of the different engine components, mainly the fuel supply system

On the other hand, it is observed that the content of JCO up to 10% does not cause significant changes on temperatures T2 and T3. Crude vegetable oils have high viscosities, low caloric value compared to diesel fuel and poor fuel atomization [27]. However, alternatives have been found such as its use mixed with diesel fuel up to 20% of oil [28]. These blends could allow the use of these alternative fuels in internal combustion engines without the need of mechanical modifications to the engine. Likewise, similar engine performance to those obtained when using only neat diesel is reported, using blends of up to 20% *Jatropha curcas* oil [6, 11, 20, 29]. This type of vegetable oil is environmentally friendly, non-toxic and has the potential to significantly reduce pollution when used in combustion engines.

The essential function of the engine's cooling system is to lower the temperature of the elements that make up the combustion chamber. The cooling liquid, in this case water, is the main responsible for the heat transfer that occurs inside the engine. Determining and studying all the variables that influence the behavior of the coolant temperature is vital to increase efficiency and durability of these systems. There are very few reports on the behavior of these temperatures when the engine uses crude vegetable oil blends (such as *Jatropha curcas*) with diesel as fuel. The variation of the temperatures of the cooling liquid of the Lister Petter LPWS2 engine with respect to the Load and the JCO is presented in Figures 4 and 5.

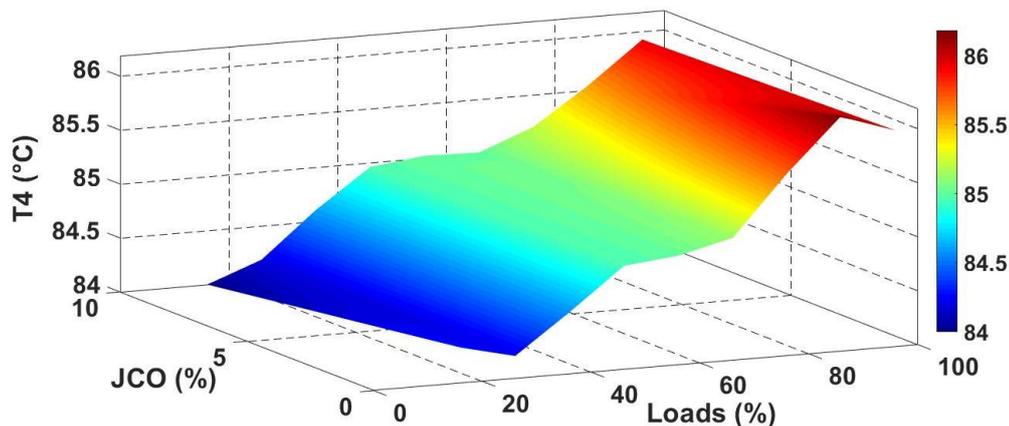


Fig.4 Response surface of T4 vs. Load and JCO

In Figures 4 and 5 can be seen that with the load increase, there is a slight increase of T4 and T5. This result is expected, since with the increase in load there is an increase of the temperatures inside the combustion chamber. The JCO content of the fuel produces a slight decrease of the cylinder temperature, which, despite not being statistically significant. The lowest temperature of the cylinder gases recorded was 168°C; this took place when the engine was operating at lower load. For this type of engine it is normal to obtain this temperature at low loads because, although in the combustion

process temperatures of up to 1000°C are obtained, when the engine operates at low loads a lesser amount of fuel is injected with respect to the amount of air supply to the chamber, which remains constant at all loads, which is why at the exit of the gases a temperature of around 170°C is obtained.

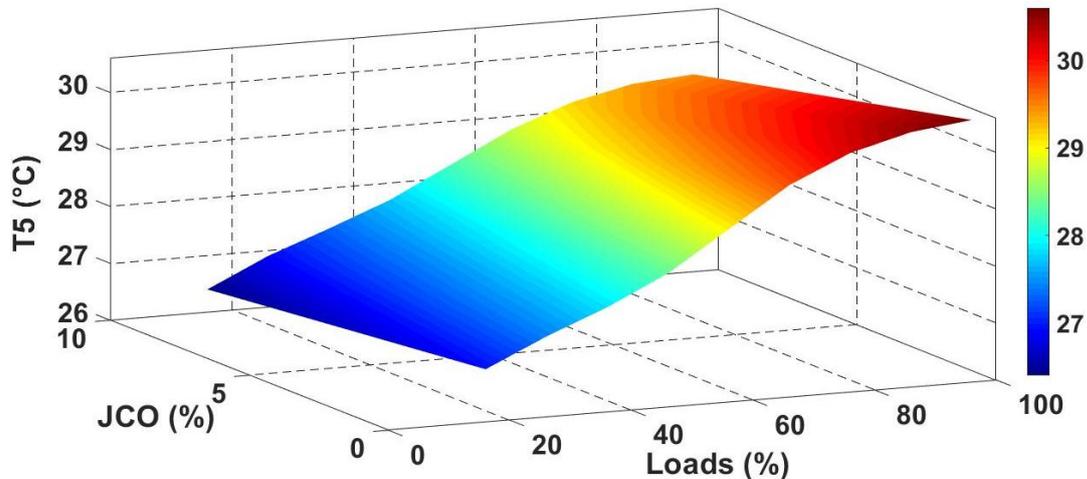


Fig.5 Response surface of T5 vs. Load and JCO

In addition, with the increase of load, the fuel intake increases, and the heat generated by friction between the moving parts of the engine is increased. This causes the cooling system to dissipate more heat which can cause slight increases of the coolant temperature at the outlet and at the inlet of the radiator.

The JCO content did not cause significant modifications in the behavior of T4 and T5. The use of this blend did not affect the behavior of the engine cooling system. By keeping the engine cooling system operating under the same conditions as with neat diesel, it is achieved: avoiding the additional formation of Nitrogen Oxides (NOx), preventing friction wear between the piston and the cylinder lines, among others. This means that despite having a lower caloric value, Jatropha oil can be used as a blend and still obtain the same benefits in this type of engine, as several researchers have suggested [30-31]. The use of a diesel blend with 10% crude Jatropha oil as fuel in a Lister Petter LPWS2 indirect injection engine did not produce significant effects on its thermal behavior. The usefulness of these results is that, in addition to being precursors in the study of ICEs working temperatures with the use of JCO blends, mathematical models will allow these temperatures to be calculated for the analyzed engine without the need of experimental test.

3. Conclusions

In this work the Response Surface Methodology was applied to study the impact of the engine load and the use of a diesel blend with 10% of Jatropha oil on the thermal behavior of an indirect injection diesel engine. Mathematical models that characterize the behavior of the main working temperatures of the engine under study were obtained. The design of experiments and the statistical analysis used allowed identifying that the most influencing parameter on the analyzed temperatures was the engine load. As the load increases, the temperatures of the exhaust gases significantly increase. The JCO content in the fuel did not cause significant changes on exhaust gas temperatures or coolant temperatures. The diesel blend with 10% Jatropha oil does not produce changes on the engine's thermal behavior.

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