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## RESPONSE SURFACE METHODOLOGY FOR PROCESS PARAMETER OPTIMIZATION OF A COAL PULVERIZER DUE TO HIGH MOISTURE CONTENT: STUDY CASE OF PECEM

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**Abstract.** *Considering the evidence of the influence of humidity on the performance of a coal-fired power plant, this research aims to answer the following questions: Which parameters of the drying process of the coal in a vertical mill have more importance to the superheated steam generator (SSG) efficiency? Does humidity (fuel and air) affect the SSG efficiency of a coal-fired power plant? To answer these questions, the Response Surface Methodology (RSM) is used to analyze and optimize the coal pulverizing system and the experimental design method used is Box-Behnken. The experiments will be performed on a model developed in the Epsilon® Professional software. The first RSM results showed that the most important parameters for the lower moisture content coal are P2, P3, and P5; for the medium moisture content coal are P2 and P5; and for the high moisture content coal are P2 and the interactions of P3\*P2 and P3\*P4. Then, the second RSM results showed the efficiency decreases with the increase of the humidity in the coal, but it did not change with the humidity of the air.*

**Keywords:** *Coal-fired Power Plant, Coal Pulverizer, Response Surface Methodology, Box-Behnken Design, Moisture content*

### 1. INTRODUCTION

Coal pulverizers are designed to reduce the size of incoming raw coal into a fine powder enabling to be burned. Before coal can be effectively burned in a superheated steam generator (SSG), different processes have to happen: coal must be crushed, dried, and moved at a minimum safe velocity. All these processes happen simultaneously and need to be connected thus allowing more efficient combustion. The maximum capacity of a pulverizer is dependent on the coal quality, how easily it grinds, how wet it is, and how fine an output the burners and furnace require.

Although power plants are designed to burn coals containing a certain percentage of moisture, a reduction in coal moisture content is attractive since it will result in significant improvements in operation and performance. On a competitive power market the efficiency and dynamic operation of fossil fuel power plants is increasing in importance. According to ? the moisture content imposes limits on the minimum load at which the coal mill may be operated and how fast the mill may change its operating point. Mainly because moisture slows down the grinding process, since a larger volume of hot air or a longer residence time for the coal in the mill is required to properly dry and grind the coal. Also, high moisture content in pulverized coal decreases the flame temperature and increase the unburned carbon fraction and NOx emissions (?).

The total moisture of the raw coal received by the pulverizer is essentially equal to the inherent moisture <sup>1</sup> plus

<sup>1</sup>Inherent moisture occurs in the microscopic structure of the coal, generally filling pores, but not visible in large fractures (?)

the surface moisture <sup>2</sup> and it is recorded on an as-received basis (?). The inherent moisture is determined by standard procedures in certified laboratories and it is provided by the coal supplier. However the surface moisture is affected by the local climate characteristics. E.g. long-term storage in good weather can help to dry out the coal before it enters the pulverizer, but can also waste valuable combustible volatile components. In contrast, outdoor storage in wet weather increases the surface moisture of the coal, which then causes flow problems and requires more hot air to dry in the pulverizer. Pulverizers cannot be exposed to extreme operation conditions to satisfy the drying process of the coal. The coal pulverizers have certain conditions to be fulfilled in order to deliver the fuel with security (?).

In literature, optimising the coal pulverizer performance of a power utility, already has been reported with different approaches. Numerical studies have been applied by ? through the use of Computational Fluid Dynamics (CFD). Rule-based algorithms as a fuzzy (?) and hybrid methods such as a neural-network and genetic algorithm (?) have been used with success. As well as, the effect of moisture on the coal pulverizing process and in the combustion process was addressed by ? and ?, respectively. Therefore, none of them combined the optimization process of a coal pulverising system with the external variables: humidity of the fuel and of the air.

Considering the evidence of the influence of humidity on the performance of a coal-fired power plant, this research aims to answer the following questions: - Which parameters of the drying process of the coal in a vertical mill have more importance to the SSG efficiency? - Does humidity (fuel and air) affect the SSG efficiency of a coal-fired power plant?

To answer these questions a robust mathematical and statistical techniques such as Response Surface Methodology (RSM) can be applied to analyze the influence of the humidity in the pulverizer process. First to understand its effects among the variables on the performance of the SSG. Then, to improve the pulverizing process. In this case, optimizing as a reference for improving the performance of the pulverizing process in order to maximize the SSG efficiency.

RSM is a popular optimization method used mostly in chemical and biochemical processes (?). The method was first introduced by ? in 1951. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response. The application of RSM to design optimization is aimed at reducing the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise. The major advantage of this technique is that it includes interactive effects among the variables and, eventually, it depicts the complete effects of the parameters on the process ?.

In this study, the RSM is used to analyze and optimize the coal pulverizing system and the experimental design method is Box-Behnken. The experiments are performed on a model developed in the Epsilon<sup>®</sup> Professional software. In sum, Epsilon<sup>®</sup> is a commercial power plant simulation software that has a library with hundreds of components that allows the development of different simulation models by coupling these components.

The main contribution of this research is the knowledge of which parameters to tune the milling system due to the moisture content in the coal and in the air. This is important to determine and control the dynamical behavior of the power plants.

## 2. METHODOLOGY

The present section aims to describe a step by step sequence of methods applied to build the model to optimize the coal pulverizer of the Pecem power plant considering the external variables: fuel moisture and weather data, as Fig. 1 present.

### 2.1 Research object

The Pecem power plant is set to produce 720 MW of electricity and it is equipped with two coal-fired SSGs, where each one designed to produce 360 MW with 1200 t/h of superheated steam at 540 °C and 18 MPa. The main object of this study is the coal pulverizer of PECSEM, capable of producing Fig. 2. shows a schematic representation of the pulverizer mill followed by the selected parameters considered in this work.

Pulverizers are designed to reduce the size of the incoming raw coal to a fineness that will result in good furnace performance. The raw coal is fed into a rotating bowl via a center feed pipe. The rate of coal feed is normally determined automatically by a combustion control system, taking into account the MW demand on the unit, coal quality, and the number of pulverizers in service. Centrifugal force causes the coal in the bowl to move radially outward, building up a bed of coal on the grinding ring. The radial and circumferential movement of the coal carries the pulverized coal up over the edge of the bowl into the path of the hot air stream. The air supplied to the pulverizer has two primary functions: hot air dries the coal; air recirculates and transports coal within the mill and to the furnace.

As the coal is continuously reduced in size, the smaller/lighter particles are swept from the bowl by the hot air. At the edge of the bowl, smaller/lighter particles of coal are entrained in the air stream and are carried upward, while dense, difficult to grind foreign material is rejected downward through the air stream into the millside. The dynamic classifier uses aerodynamic and centrifugal forces to separate the fine output product from the larger particles. As the particles approach the dynamic classifier, they meet centrifugal forces that throw the particles outward. At the pulverizer exit, the

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<sup>2</sup>Surface moisture adheres to the outside of a coal sample or particle, it is that part of the total moisture over the inherent moisture (?).

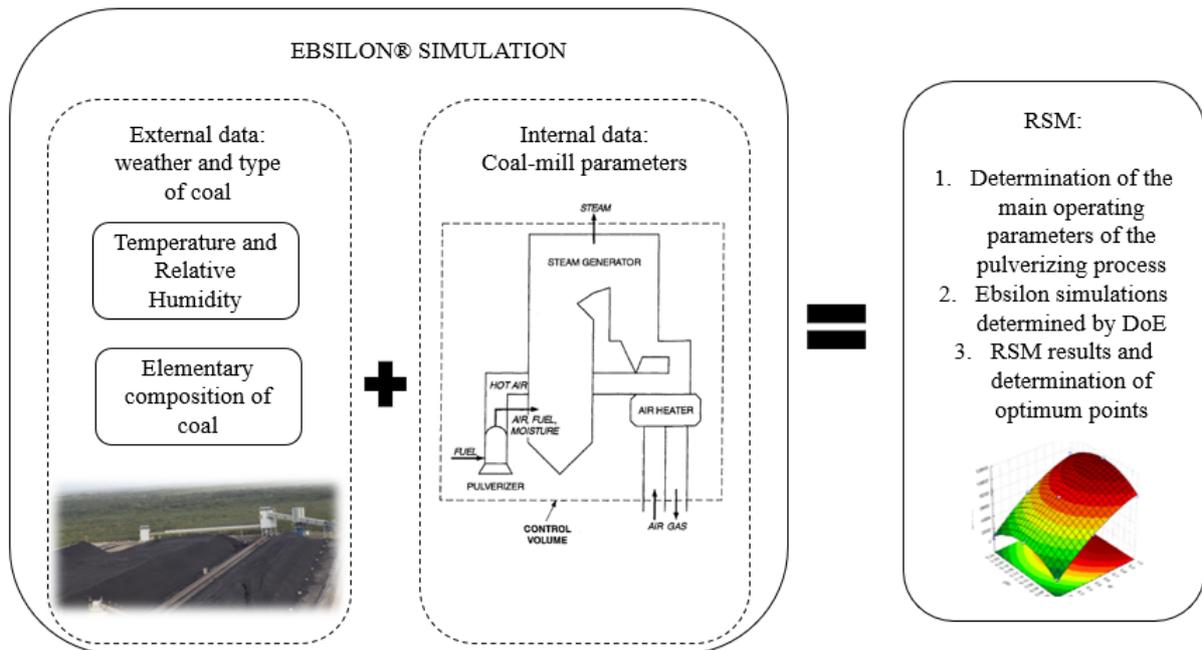


Figure 1. Methodology graphical abstract  
Source:personal archives.

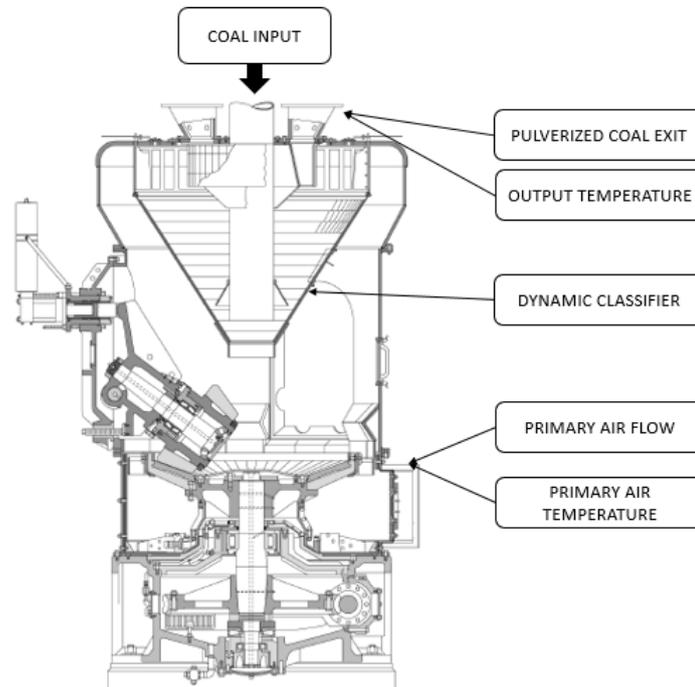


Figure 2. Mill main paramters  
Source:personal archives.

coal-air stream is distributed directly to the coal pipes.

## 2.2 Determination of the input and output parameters and their levels

In order to choose the input and output parameters an interview with the coal-mill operator expert was made first. This preview was very import to guide the data acquisition, because the coal-mill has more than 58 measured data used by the system operator in its control.

The external inputs considered in the simulation were the air and the fuel with different humidity levels. The humidity in the air means the quantity of water vapor present in the air and it can be expressed as an absolute, specific, or relative value. For a given ambient temperature, relative humidity (RH) is defined as the ratio of the observed vapor pressure to the saturation vapor pressure at the same conditions (?). So, to estimate the mass fraction of water in the air it was calculated through the simple procedure for calculating atmospheric water vapor concentration made by ?.

To simulate the inherent moisture of the fuel three different types of coal were selected, one with lower moisture content, other with a medium moisture content, and the last one with a high moisture content, as shown in the Tab. 1.

Table 1. Elemental composition of coal by type of simulated coal

	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Humidity (H2O)
Coal_low_moisture	0.734935	0.047	0.12	0.014	0.006	0.000765	0.0773
Coal_medium_moisture	0.681583	0.043	0.1084	0.012	0.0062	0.000717	0.1481
Coal_high_moisture	0.573821	0.0521	0.1555	0.013	0.00336	0.000819	0.2014

The internal parameters, also called factors, were selected from a large data set due to its controllability by the operators. Controllable parameters present an independent behavior among each other and can be manipulated by manual command. The only exception is the air relative humidity which is not controllable, however it is fundamental for the analysis of the effect of the moisture in the drying process of the coal mill carried out in this study. The Tab. 2 shows the input parameters selected for the RSM modeling and optimization. It is important to note that only the controllable parameters (P2 to P5) were used for optimization. The output parameters chosen were the SSG efficiency (%).

Table 2. Model input parameters (internal and external) and levels

Parameter	Measured unit	Minimum (level -1)	Mean (level 0)	Maximum (level 1)
P1: Air relative humidity (uncontrollable)	%	0	50	100
P2: Mass flow air mill (controllable)	kg/s	21	23.5	26
P3: Primary air temperature (controllable)	°C	150	215	280
P4: Mean diameter of coal (controllable)	µm	25	50	75
P5: Mill output temperature (controllable)	°C	65	75	85

### 2.3 Ebsilon model of the coal mill of PECEM

Ebsilon® Professional is a commercial power plant simulation software that has a library with hundreds of components, allowing to build models by coupling these components. The Figure 3 presents the model that uses the mill component provided by the software coupled with a detailed Pecém boiler model.

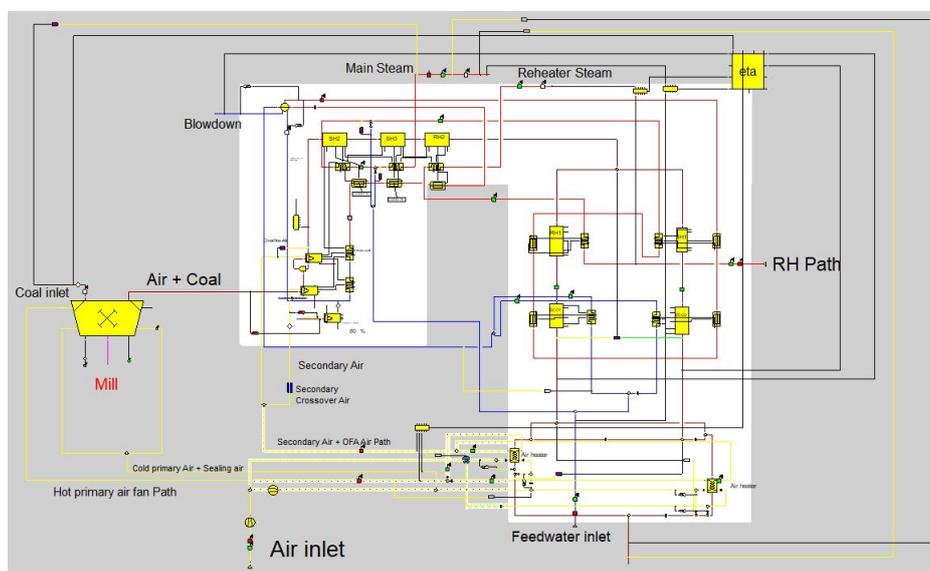


Figure 3. Simulation model with the mill and the SSG  
 Source:personal archives.

The mill model has five main inlets, shown in Table 2, and two outlets. The raw coal input is dried by a mixture of two air flows (P2), this mixture is composed by a hot and another cold flow, this allows to set the desired drying temperature (P3). The outlet temperature of the ground coal (P5) its also set. By a thermodynamic balance that takes into account the coal (Tab. 1) and air composition, the amount of residual water in the coal and in the air that leaves the mill are calculated.

The mill flow outlet is connected to the combustion chamber inlet of the boiler model. In order to compare the impact of different humidity and coal types on the boiler efficiency, the energy in the main steam outlet of the boiler was fixed and the inlet flow of raw coal in the mill needed to reach that energy was calculated by iteration.

## 2.4 RSM

RSM consists of a group of mathematical and statistical techniques that can be used to define the relationships between the response and the independent variables (?). The sequential nature of RSM allows the experimenter to learn about the process under study as the investigation proceeds and over the course of the RSM application it will be able to answer the questions (?): (1) the location of the region of the optimum, (2) the type of approximating function required, (3) the proper choice of experimental designs, (4) how much replication is necessary, and (5) whether or not transformations on the responses or any of the process variables are required.

Because a response surface study has multiple stages with different goals, it is possible to separate an optimization into three main stages.

1. Determination of the independent parameters and their levels: in this step the controllable parameters and the operating ranges or levels were determined based on the experience of the operator of the mill at the PECCEM plant.

2. Selection of the experimental design and carrying out the experiments: The chosen design model was Box-Behnken. The simulations were carried out in the Epsilon model of the PECCEM coal mill (subsection 3.3).

3. Response surface plot and contour plot and determination of optimum points: Minitab software was used to analyse the results.

The relationship between the response and the input is given in Eq. (1) (?):

$$y = f(x_1, x_2, \dots, x_k) \quad (1)$$

where  $y$  is the response,  $f$  is the unknown function of response,  $x_1, x_2, \dots, x_k$  denote the independent variables, also called factors,  $n$  is the number of the independent variables.

In this study, the Box–Behnken experimental design was chosen for finding out the relationship between the response functions and variables. Box–Behnken design is rotatable second-order designs based on three-level incomplete factorial designs (?). Which requires an experiment number according to  $N = k^2 + k + cp$ , where ( $k$ ) is the factor number and ( $cp$ ) is the replicate number of the central point (?). Box–Behnken is a spherical, revolving design. Viewed as a cube, it consists of a central point and the middle points of the edges.

A Box–Behnken design with three levels was utilized to evaluate the effect of parameters on the residual moisture in fuel and in the efficiency of the SSG. So these three independent parameters were coded at three levels that is +1, 0, and 1 with same step size, where +1 represents the maximum value, 0 represents to the center, and 1 represents the minimum value of each parameter, which are considered for analysis.

The goal is to optimize the response variable  $y$ . It is assumed that the independent variables are continuous and controllable by experiments with negligible errors. It is required to find a suitable approximation for the true functional relationship between independent variables and the response surface. Usually a second-order model is utilized in response surface methodology Eq. (2).

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where  $x_1, x_2, \dots, x_k$  are the input factors which influence the response  $y$ ;  $\beta_0, \beta_{ii}$  ( $i = 1, 2, \dots, k$ ),  $\beta_{ij}$  ( $i = 1, 2, \dots, k; j = 1, 2, \dots, k$ ) are unknown parameters and  $\varepsilon$  is a random error. The  $\beta$  coefficients, which should be determined in the second-order model, are obtained by the least square method. In general Eq. (2) can be written in matrix form Eq. (3).

$$Y = bX + \varepsilon \quad (3)$$

where  $Y$  is defined to be a matrix of measured values,  $X$  to be a matrix of independent variables. The matrixes  $b$  and  $\varepsilon$  consist of coefficients and errors, respectively. The solution of Eq. (3) can be obtained by the matrix approach Eq. (4).

$$b = (\chi' \chi)^{-1} \chi' Y \quad (4)$$

where  $\chi'$  is the transpose of the matrix  $\chi$  and  $(\chi' \chi)^{-1}$  is the inverse of the matrix  $\chi' \chi$ .

### 3. RESULTS

The first step in the development of this research was to develop the simulation of the components studied in this research, coal mill and SSG, in the Epsilon software in order to simulate the behavior of the PECEM power plant. Then the Box-Behnken design and the RSM were applied in two steps. For each Epsilon simulation, it was used the Box-Behnken design to estimate the simulations for the 4 controllable factors in Tab. 2. Subsequently, the Box-Behnken design estimated the simulations for the 5 factors (4 controllable and 1 uncontrollable) in Tab. 2, the results of the Box-Behnken are described in Tab. 3. Both simulations (4 and 5 factors) were applied for each type of coal mentioned in the Tab. 1, in total it was carried out six times.

Table 3. Simulation determined by the Box-Behnken design for 4 and 5 parameters

4 factors		5 factors	
Number of factors	4	Number of factors	5
Number of runs	27	Number of runs	46
Number of blocks	1	Number of blocks	1
Replication	1	Replication	1
Total number of runs	27	Total number of runs	46
Center points	3	Center points	3

The results of the experiments were subjected to variance analysis (ANOVA) for both the response variables with a 95% confidence level (p-value of models under 0.05 were considered).

Next subsections will present the results for the 5 factors simulation for each kind of fuel with the efficiency of the SSG as the output. The purpose is to first analyze if the moisture (fuel and air) has an effect on the performance of the SSG and to identify which parameters have more importance in the drying process of the coal in a vertical mill. Then, to improve the coal mill performance the optimization of the simulation with the 4 controllable factors and also with the efficiency of the SSG as the output are presented.

#### 3.1 Low moisture content fuel

From the experimental results listed in Tab. 3, the response function representing the relationship between the parameters and the efficiency of the SSG presented a R square of 96.1%. In this case the most relevant parameters (with p-value lower than 0.05) were P2, P3, and P5, the factorial main effect plot, Fig. 4, shows the behaviour of each one.

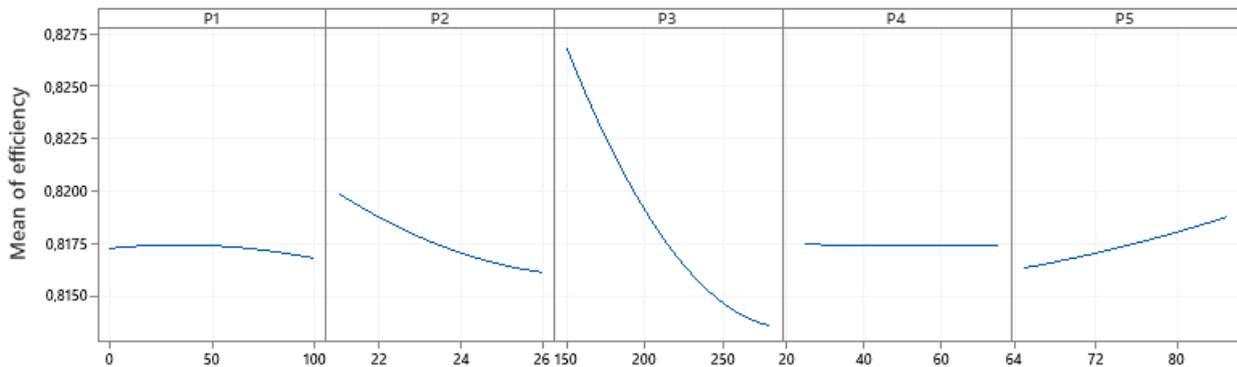


Figure 4. Main effect plot for Efficiency output  
 Source:personal archives.

All the parameters showed to be important to the SSG efficiency, with primary air temperature (P3) the one that impacts the most on the result with a negative correlation. That is, the lower the temperature, the greater the generator efficiency. Considering the importance of parameters P3 and P5 in the efficiency a surface plot was made to visualize the optimal points of the parameters and their interaction, Fig. 5.

The Fig. 5 shows the clearest part as the region that obtains the best efficiency results from the SSG considering P3 and P5. As the opposite, the darker region shows the relation of the parameters with less efficiency to the SSG. The result also shows that the relationship between the parameters and the output is not linear. Therefore, more difficult to be controlled by the system operator

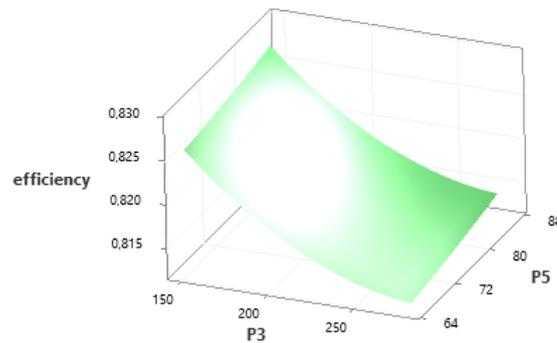


Figure 5. Surface plot of residual moisture interaction with P3 and P5  
Source:personal archives.

### 3.2 Medium moisture content fuel

From the experimental results listed in Table 3, the response function representing the relationship between the parameters and the efficiency of the SSG presented a R square of 88.7%. In this case the most relevant parameters (with p-value lower than 0.05) were P2 and P5, and the interactions of P2\*P5, Fig. 6, shows the behaviour of each one.

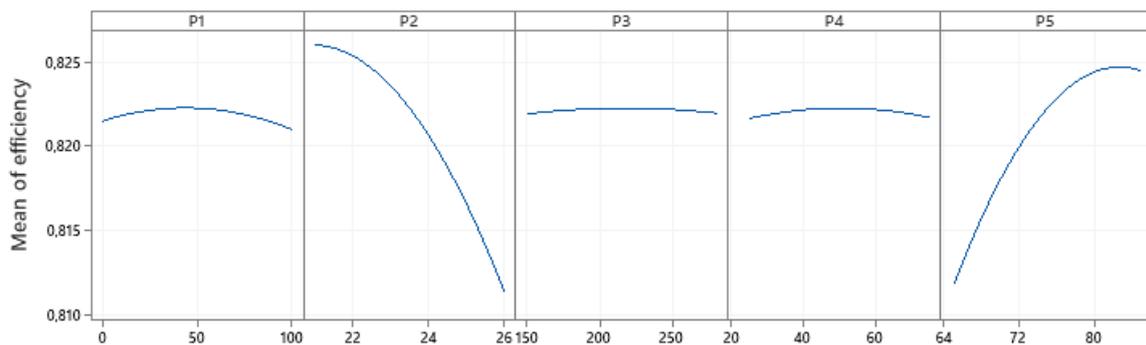


Figure 6. Main effect plot for Efficiency output  
Source:personal archives.

All the parameters showed to be important to the SSG efficiency. The primary air flow (P2) and the coal mill output temperature (P5) presented higher impact on the result with opposite behaviour, the P2 has a negative correlation and P5 has a positive correlation. These results can show that with the increase in moisture in the coal the higher the outlet temperature reduces the amount of moisture in the fuel. At the same time, the higher the primer flow rate, the better the drying of the coal. Considering the importance of parameters P2 and P5 in the efficiency a surface plot was made to visualize the optimal points of the parameters and their interaction Fig. 7.

The Fig. 7 shows the clearest part as the region that obtains the best efficiency results from the SSG considering P2 and P5. As the opposite, the darker region shows the relation of the parameters with less efficiency to the SSG. The result also shows that the relationship between the parameters and the output is not linear. Therefore, more difficult to be controlled by the system operator. Compared to the surface plot of the lower moisture coal, the dark region is much larger than the light region. Therefore, indicating the decrease in the optimization region of the most important factors.

### 3.3 High moisture content fuel

From the experimental results listed in Table 3, the response function representing the relationship between the parameters and the efficiency of the SSG presented a R square of 62.0%. In this case only P2 presented p-value lower than 0.05 and the interactions of P3\*P2 and P3\*P4, Fig. 8, shows the behaviour of each one.

Also in this case all the parameters showed to be important to the SSG efficiency, with the primary air flow rate (P2) the one that impacts a little more on the result with a negative correlation. Despite individually presenting a minor impact, all other parameters showed a non-linear behavior with the efficiency of the SSG as can be seen in Fig. 8. This result indicates that with the increase of the humidity in the coal and in the humidity of the air the complexity of the operation

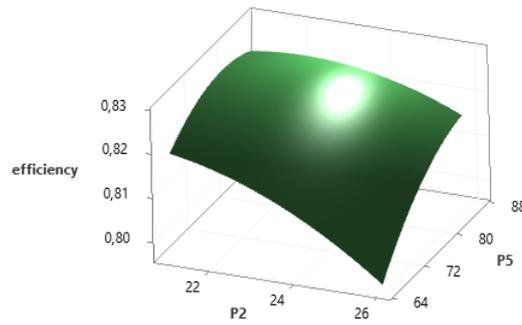


Figure 7. Surface plot of residual moisture interaction with P2 and P5  
 Source:personal archives.

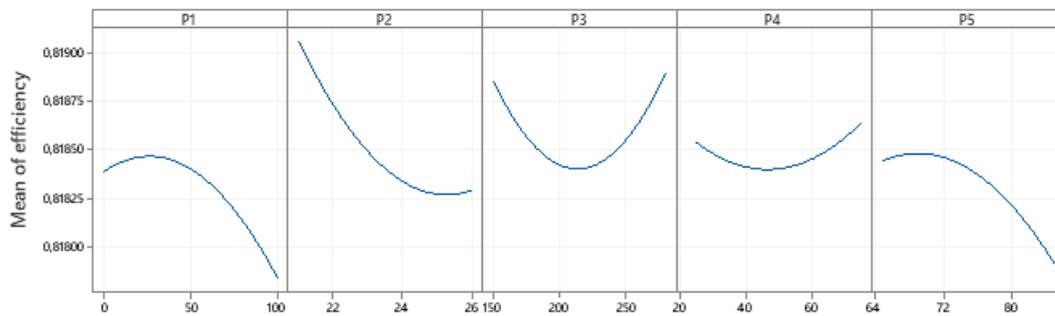


Figure 8. Main effect plot for Efficiency output  
 Source:personal archives.

of the coal mill increased much more. Considering the importance of parameters P2 and P3 in the efficiency a surface plot was made to visualize the optimal points of the parameters and their interaction Fig. 9.

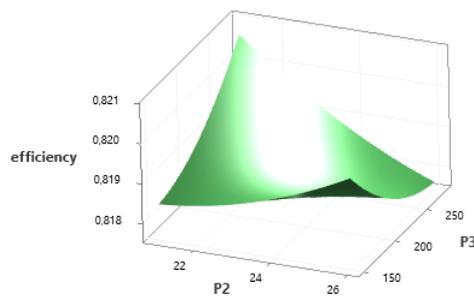


Figure 9. Surface plot of residual moisture interaction with P2 and P5  
 Source:personal archives.

The Fig. 9 shows the clearest part as the region that obtains the best efficiency results from the SSG considering P2 and P3. As the opposite, the darker region shows the relation of the parameters with less efficiency to the SSG. The result also shows that the relationship between the parameters and the output is not linear. Therefore, more difficult to be controlled by the system operator. Compared to the surface plot of the medium moisture coal, the light region is much larger than the dark region, but still smaller than the region with less humidity.

### 3.4 Optimization

Finally, Fig. 10, Fig. 11, and Fig. 12 show the parameters that maximize the SSG efficiency through the optimization of the coal mill parameters for each type of coal.

According to Fig. 10. the maximum efficiency obtained for the coal with lower humidity was 83.09%, and the multiple response prediction are: P2: 21 kg/s; P3: 150 °C; P4: 75 μm; P5: 85 °C.

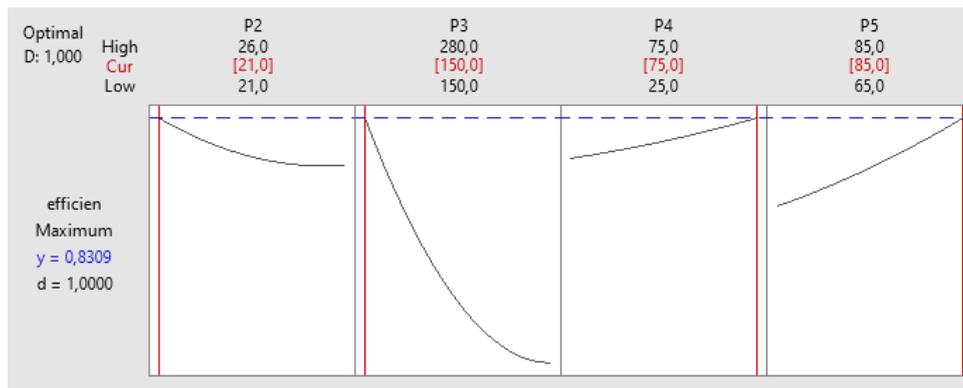


Figure 10. Multiple response prediction to maximize the efficiency of the SSG fueled with low moisture coal  
Source:personal archives.

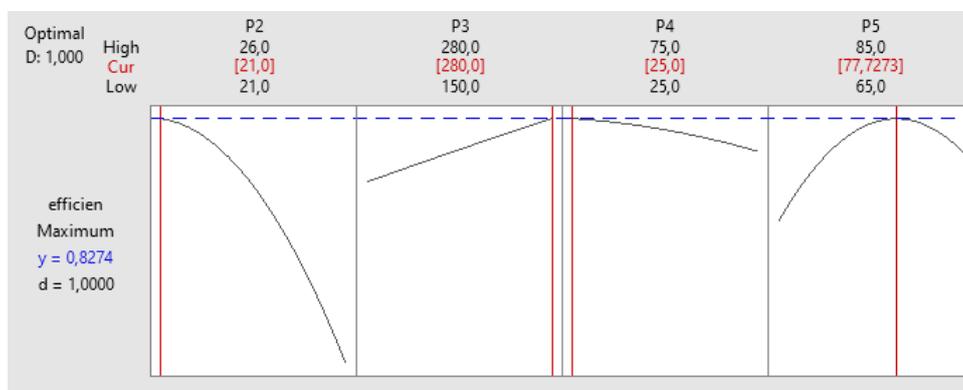


Figure 11. Multiple response prediction to maximize the efficiency of the SSG fueled with medium moisture coal  
Source:personal archives.

According to Fig. 11. the maximum efficiency obtained for the coal with lower humidity was 82.74%, and the multiple response prediction are: P2: 21 kg/s; P3: 280 °C; P4: 25 μm; P5: 77.73 °C.

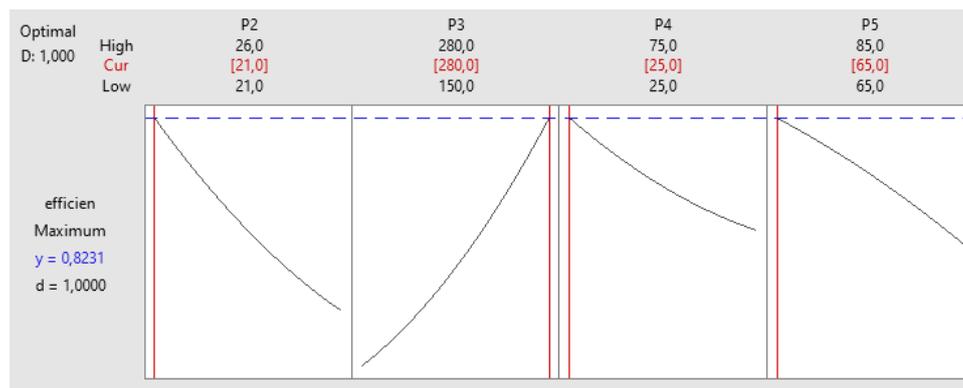


Figure 12. Multiple response prediction to maximize the efficiency of the SSG fueled with high moisture coal  
Source:personal archives.

According to Fig. 12. the maximum efficiency obtained for the coal with lower humidity was 82.31%, and the multiple response prediction are: P2: 21 kg/s; P3: 280 °C; P4: 25 μm; P5: 65 °C.

#### 4. CONCLUSION

To explore the effects of the 5 parameters presented in Tab. 2. on the efficiency of the SSG, 46 flotation experiments were carried out in an Epsilon model of the PECEM Power Plant. The RSM results for this simulation showed that the most important parameters for the lower moisture content coal are P2, P3, and P5; for the medium moisture content coal are P2 and P5; and for the high moisture content coal are P2 and the interactions of P3\*P2 and P3\*P4.

Then, the second DoE simulation (Tab. 3) for the 4 controllable factors, presented in Tab. 2, made it possible to find the answer for the effect of the moisture, both on coal and in the air, on the efficiency of the SSG. The RSM results showed that maximum efficiency for the lower moisture content coal are 83.09%; for the medium moisture content coal are 82.74%; and for the high moisture content coal are 82.31%. So, the efficiency decreases with the increase of the humidity in the coal, but it did not change with the humidity of the air.

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## **6. REFERENCES**

## **7. RESPONSIBILITY NOTICE**

The authors Natália de Assis Brasil Weber, Augusto Delavald Marques, Julian David Hunt, Paulo Smith Schneider and Júlio Cezar Mairesse Siluk are solely responsible for the printed material included in this paper.