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# Surrogate modeling approach to standardize a steam generator operation – a case study of the PECEM power plant

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**Abstract.** Coal-fired power plants provides about 40% of electricity worldwide and should be in line with the stringent environmental control requirements and continuous efficiency enhancement. Actions towards high-quality operation can be supported by the fine modeling of plant systems in order to aid field operation. The present work proposes the standardization of operation through surrogate models to represent the assembly of the steam generator and its mills, based on the system simulation by the EBSILON commercial software. A methodology for the construction of a surrogate model to a coal-fired power plant in operation is proposed and applied to the case study of the PECEM power plant. Design of Experiments (DoE) and Response Surface Methodology (RSM) are used to identify the model main controllable parameters and interactions to then rank them by order of importance. The surrogate model based on the commercial software is built to simulate the system efficiency with seven controllable input parameters: primary airflow, pulverized coal outlet temperature, stoichiometry, excess O2, secondary, and primary air crossover duct pressure, ranked by descendent significance. The maximum relative deviation of that surrogate model compared to the software simulation is 0.0172. The best operating ranges by each controllable parameter are proposed.

**Keywords:** Coal-fired power plant, Design of Experiments, Response Surface Methodology, Surrogate Model

## 1 Introduction

A coal-fired power plant is a complex system of interconnected processes that converts chemical energy into electricity. Power plant operation effectively takes place at the steam generator, as no other action on the remaining equipment can impact the overall performance to the same level [1, 2]. The control system handles plant stability, leaving the operator to manage controllable losses [3].

An experienced operator knows the plant characteristics and develops its particular way of command that guarantees the system integrity and performance. Although effective, there is room for reducing variability and improving the system performance process standardization, by means of decision support tools. These tools may be based on computational representations able to simulate the system behavior in a broad range of conditions, also called surrogate models. The one developed in the present work was based on the Design of Experiments (DoE) and Response Surface (RSM) methodologies to standardize the steam generator and its mills operation to suggest operating conditions to the operator. The procedure to conduct DoE is applied to a simulation model of the PECEM power plant, located in São Gonçalo do Amarante, Ceará. The proposed methodology can be applied to other generation plants.

## 2 System Description

PECEM I [1] is composed by two independent sub-critical coal-fired power units of 360MW electric power output each. The identical steam generators are equipped with heat exchangers such as superheaters, reheaters, economizers and air heaters, arranged to efficiently absorb heat released by fuel combustion and deliver steam at rated temperature, pressure and capacity. These last parameters determine the steam generator configuration [1, 2]. Three independent mills feed one steam generator with dry pulverised coal. In fact, there are four mills available but one of them serves as a backup.

## 3 Modeling approach

The methodology proposed in the present work follows three phases: planning and execution of the experiments with DoE, model fitting through RSM, and result analysis to build a surrogate model representing the system.

### 3.1 Planning and execution - DOE

The design matrix with the necessary experiments to be carried out at the power plant is defined. The control volume (step 1) defines the scope of the study and its boundaries, by selecting the whole plant or some subsystem, such as the steam generator. Steps 2 to 4 follow the well known DoE procedure, and allows to chose the experimental design method in step 5. It must balance the amount of experiments with the available time and resources to conduct them, by taken into account the factor types and nature, replication, and blocking. The resulting design matrix contains the controlled factors, their levels and the experiment running order. The sixth step deals with procedures for conducting the experiments at the power plant.

### 3.2 Model fitting - RSM

The model fitting builds a response surface model (RSM) out from the collected data. The seventh step employs Analysis of Variance (ANOVA) with the aid of MINITAB® to test the hypothesis defined at the beginning of the study, based on the definition of a confidence interval, and its complementary significance level $(\alpha)$. The interactions between factors are tested in step 7, starting with the higher-order interactions. The null hypothesis $H_0$ is rejected for p-value¡$\alpha$, meaning that the interaction is significant, otherwise (p-value¿$\alpha$) the interaction is removed from the model and the process restarted. This step is repeated until all remaining interactions in the model are considered as significant. Next, it is tested the significance of individual factors. The null hypothesis $H_0$ is rejected for p-value¡$\alpha$, which indicates that the effect of a given factor is significant. At the end of the seventh step, only the significant terms according to the response remain in the model. The second-order polynomial model is fitted in step 8.

Step nine contains the residual analysis to check the model assumptions of normality, constant variance, and independence. The simplest model that produces random residuals is a good candidate for a relatively precise and unbiased model. If some of the model assumptions could not be verified, the conduction of new analysis would become necessary. The possibilities include a missing variable, a missing higher-order term of a variable in the model to explain the curvature or a missing interaction between terms already in the model [4, 5].

### 3.3 Synthesis - surrogate model

The last phase builds a surrogate model to standardize the operation based on the analysis of the results of the previous steps. The first action concerns ranking the factors (controlled parameters) in descending order of importance in the response, in order to determine the optimal settings that minimizes variability. Key parameters are identified and ranked on a Pareto plot at the tenth step.

The $11^{th}$ step is the construction of the main and interaction effects plot to analyze factors behavior. This is necessary to determine the settings that yield the best performance to improve steam generator efficiency. Step $12^{th}$ settle operating ranges to divide the regions in which the important factors lead to the best possible response. The lines of constant yield are connected to form response contours using contour plots. These contours are projections on the interest regions [5].

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[1] https://pecem.brasil.edp.com/en/power-plant.

The $13^{th}$ step defines the surrogate model as the final equation of the previous steps, which assures that only the significant terms are present. The $14^{th}$ step tests the proposed surrogate model to it is validation. New predictions are made at certain positions within the design space where no data points existed previously. In closing, the surrogate model is used in $15^{th}$ step to provide a sequence of maneuvers to the operator considering only the significant factors (controllable parameters). The operator order of action is defined according to the importance of the factor and the best operational ranges by factor are settled ensuring a standardized operation.

## 4 Case study of the PECEM power plant

The modeling approach presented in section 3 is applied to the case study of the PECEM power plant. The power plant assessment was carried out for the 360 MW eletrical output base load, as factor levels can display different ranges according to the plant load. It is worth recalling that the research goal is to standardize the steam generator operation in order to improve its performance and thereafter impact the plant overall behaviour.

The natural choice of control volume (CV) is around the steam generator, but mills were included as they are directly related to the system performance. Considering the objective of standardizing operation to reduce process variability related to the operator action, it is mandatory to identify which parameters are significant to the response. The significance of the controllable parameters and their interactions are the hypothesis to be tested.

The selection of the response and factors began with the identification of critical process parameters. In this study, the interest is in characterizing the efficiency of the steam generator as the response. The efficiency is capable of representing the performance of the steam generator in a single parameter and for this reason was selected. The factors (controllable parameters) selection requires the assurance of controllability and independence between them. System parameters are identified using equipment identification codes (KKS). The initial list of parameters considered three sources: boiler-related KKS filter, 3, and advising from PECEM technical staff. The classification was based on controllable and uncontrollable parameters. The controllable parameters by definition can be directly impacted by the actions of the unit control operator [3].

## 5 Simulation Model

Figure 1 represents the EBSILON implementation of the PECEM steam generator and mills.

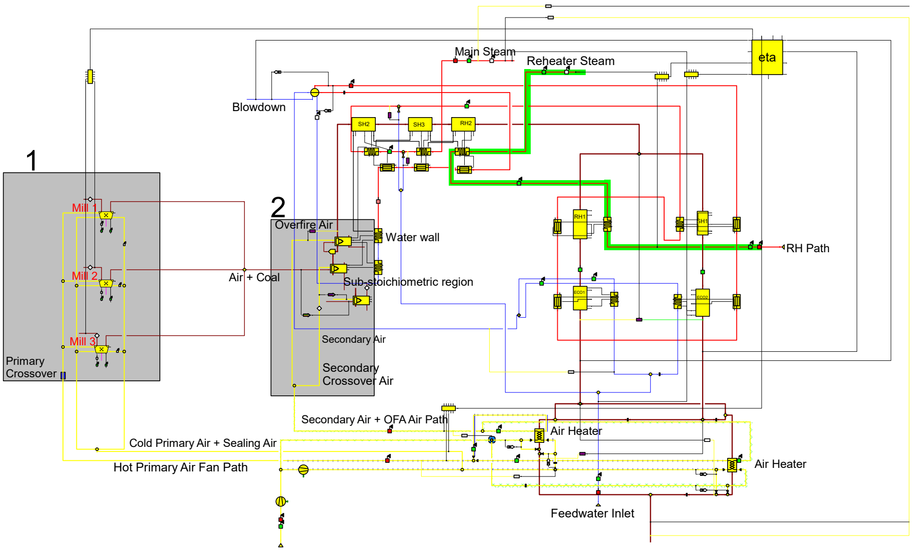

Figure 1. Representation of the PECEM steam generator simulation in the EBSILON® simulation program.

The complete system is composed by the steam generator, three mills and auxiliary equipment as heat exchangers, pumps and tanks, connected by working fluid and fuel streams, modeled by 149 components. Two special subsystems are highlighted in the Figure 1 for the mills (1) and the steam generator furnace (2). Subsystem 1 input parameters were defined as hot and cold primary air, coal flow and sealing air, coal and air mixture outlet temperature.The outputs are the fuel air mixture and it is moisture. Subsystem 2 segregates two volumes with different models to calculate the sub-stoichiometric combustion and a complementary one, with excess air, in the burnout zone. Inputs are the secondary air and over fire air (OFA) flow rates and outputs are the flue gases sent to the heat exchangers and the steam generation rate.

### 5.1 Model assessment

Simulated results from the EBSILON model were compared to experiments performed at the PECEM power plant. The results to the steam generation efficiencies of the PECEM power plant for different input conditions are presented in Table 1.

Table 1. Relative deviation of real experiments at the PECEM power plant and the simulation model

| **Steam Generator Efficiency (S1)** | | | |
|---|---|---|---|
| Experiment number | PECEM power plant | Simulation model | Relative deviation |
| 1 | 84.19% | 83.52% | 0.80 |
| 2 | 84.37% | 83.53% | 1.00 |
| 3 | 84.02% | 83.00% | 1.21 |
| 4 | 82.89% | 83.00% | -0.13 |
| 5 | 83.90% | 83.52% | 0.45 |
| 6 | 83.61% | 82.81% | 0.96 |
| 7 | 83.19% | 82.80% | 0.47 |
| 8 | 83.76% | 83.52% | 0.29 |
| 9 | 82.92% | 82.79% | 0.16 |
| 10 | 82.82% | 83.49% | -0.82 |
| 11 | 83.71% | 83.46% | 0.30 |

The relative deviation was calculated by the ratio between the efficiency difference of the PECEM plant and the simulation model in relation to the PECEM plant efficiency. Efficiency displayed a 1.55% variation for the actual case and no more then 0.53% for the simulation model, which is a controlled and conservative environment.

### 5.2 DoE applied on the simulation model

The simulation model considered as controllable parameters the primary air flow (P1), pulverized coal outlet temperature (P2), stoichiometry (P4), excess $O_2$ (P5), secondary air crossover duct pressure (P6), primary air crossover duct pressure (P7). Of the six factors, two concerns the mills (P1 and P2) and the remaining ones are related to the steam generator. The operating range of the selected factors (controllable parameters) are determined according to the plant history to provide safe and stable conditions.

Table 2 summarizes the main values collected for the controllable parameters for group 2 operating on the 340 to 360 MW range. It can be noticed that ranges are somehow limited but it always tried to reach the compromise of improving efficiency by respecting plant safety.

The Box-Behnken design (BBD) was chosen as the DOE. The experiments results for steam generator efficiency (S1) were performed in the simulation model and are presented in Table 4 at the Appendix. Efficiency ranged 3.19% in absolute values, which is quite sensitive for that response factor.

### 5.3 Fitting the second-order model

The next steps on the process were to model the response surface (RSM) fitting the steam generator efficiency (S1) in a second-order model. The terms presents in the model contain only the terms statistically significant according to the Analysis of Variance (ANOVA). Significant factors and interactions were selected by searching terms with p-value¡$\alpha$=0.05, which reject the null hypothesis and corresponds to a minimum confidence level of

Table 2. Summary of factors (controllable parameters) operation range and respective levels

| Factor | Lower Level | Medium Level | Upper Level | Description |
|---|---|---|---|---|
| P1 (kg/s) | 24.0 | 26.0 | 28.0 | Primary air flow |
| P2 (°C) | 65 | 75 | 85 | Pulverized coal outlet temperature |
| P4 (dimensionless) | 0.80 | 0.88 | 0.95 | Stoichiometry |
| P5 (%) | 1.5 | 2.3 | 3.0 | Excess $O_2$ |
| P6 (mbar) | 18 | 21 | 23 | Secondary air crossover duct pressure |
| P7 (mbar) | 70 | 78 | 85 | Primary air crossover duct pressure |

95%.

The equation 1 presents the final model.

$$
\begin{aligned}
&S1 = 43.44 + 0.1604P1 + 1.22355P2 - 14.54P4 - 0.4101P5 \\
&- 0.128P6 - 0.0228P7 - 0.002193P1^2 - 0.007614P2^2 + 8.394P4^2 \\
&- 0.04651P5^2 + 0.003144P6^2 + 0.000147P7^2 - 0.062P1P4 - 0.01172P1P5
\end{aligned}
\tag{1}
$$

The final model displayed an adjusted $R^2$ of 99.98% and a predicted $R^2$ of 99.95% which can be considered suitable to calculate S1 [6].

The Pareto chart presented in Figure 2 was analyzed to rank the factors that most influence variability in the response S1.

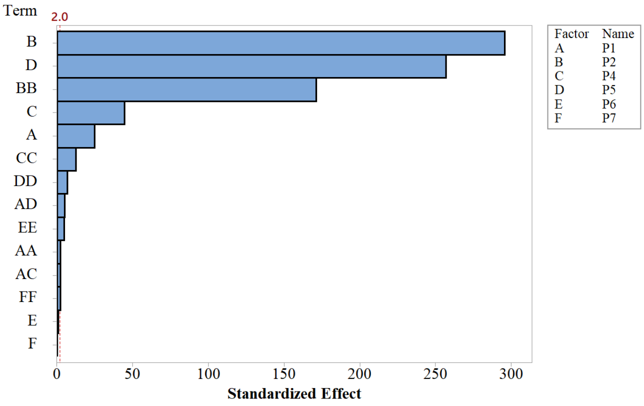

Figure 2. Pareto chart of the standardized effects (response S1, $\alpha$=0.05)

Factors by order of importance in respect to the system efficiency (S1) were the pulverized coal outlet temperature (P2), excess $O_2$ (P5), stoichiometry (P4), primary air flow (P1), secondary air crossover duct pressure (P6), and primary air crossover duct pressure (P7). Single effect on the steam generator efficiency (S1) in respect to each factor are displayed in Figure 3. Both a main effects plot and a Pareto plot are used to identify the key process parameters or factors which have an impact on variability.

The slope is proportional to the effect. Factors P2 and P5 displayed a significant impact on S1 variation, confirmed on the former Pareto chart (Figure 2) which ranked the factors P2 and P5 in the first and second position, respectively. The steam generator efficiency (S1) increases as the primary air flow (P1), stoichiometry (P4) and excess $O_2$ (P5) decrease. In the burning process, the more air is presented the greater the energy is used to promote

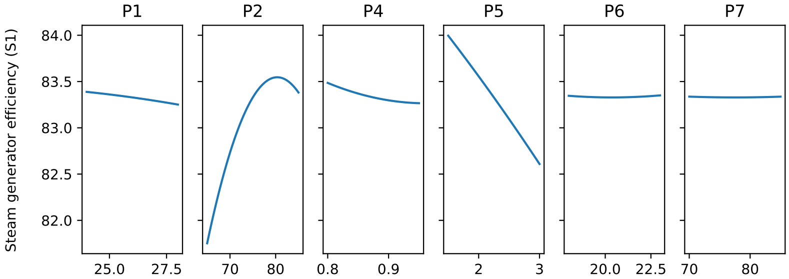

Figure 3. Main effects plot for the response steam generator efficiency (S1)

the combustion. It is worth remembering that the stoichiometry (P4) is related to the sub stoichiometry region while the Excess $O_2$ (P5) is related to the burnout zone. Regarding the pulverized coal outlet temperature (P2) the higher the temperature of the pulverized coal the better for the burning process. This temperature must be high enough to remove coal moisture, however, it cannot be so high as to cause the auto-ignition process.

## 6 Surrogate model definition

The surrogate modeling technique used in the present work was the Polynomial Response Surface (PRS) based on DoE and RSM. The second-order model was chosen to predict the steam generator efficiency S1, presented in Equation 1. The surrogate model substitutes more sophisticated models and its validity is constrained to the range of the selected factors presented in Table 2.

The generated surrogate model was tested for different situations and results were compared to the ones forming the BBD 54 experiments. In that context, the highest relative deviation was 0.0183 (Appendix - Table 5). The generated response surface produces 20 predictions for new and untested operational conditions, willing to assess the model accuracy for unknown states (Appendix Table 6). Factors were randomly varied to represent twenty new operational conditions. The maximum relative deviation was found to be 0.0172. Results show a slightly larger relative deviation for these new operating conditions.

For the suggestion of a sequence of maneuvers there are no further constraints except the factors limits. The proposal of this section is to define the factors values of operation to improve steam generator performance. The desired operational conditions to operate the steam generator efficiency (S1 = 84.43%) corresponds to maximum value of P6 = 23 mbar, minimum values of P1 = 24 kg/s, P4 = 0.8, P5 = 1.5 %, and P7 = 70 mbar, and an intermediate value for P2 = 80°C.

The steam generator efficiency varies from 80.80 to 84.43%. If the best operating conditions are defined as those with steam generator efficiency above 84% a set of input conditions can be chosen. Table 3 presents the possible operating conditions to guarantee steam generator efficiencies above 84% which is only possible for P2 above 75°C and P5 below 2.0%.

The most important factors according to the rank presented in Section 5.3 were the pulverized coal outlet temperature (P2) and the excess $O_2$ (P5). If the levels of these factors are kept constant at their optimum, the other factors may vary throughout their operating range but the steam generator efficiency will always remain above 84%. If P5 is set in 2% the factors P1, P4 and P6 must be kept at their optimum conditions to assure efficiencies above 84%. On the other hand, if the temperature drops to 70°C, regardless of the operating range of the other factors the steam generator efficiency will not reach values greater than 83.62%. This could indicate high moisture content which proves the difficulty of maintaining stable and high steam generator performance on rainy days.

## 7 Conclusions

The current work aimed to improve steam generator performance through process standardization. The proposed methodology applied RSM based on the DoE approach to build a surrogate model capable of capture the behavior of a coal-fired power plant system focused on the steam generator and its mills across a defined design space.

A simulation model based on mass and energy balances were developed to represent the PECEM power plant and perform the experiments proposed by DOE. The steam generator efficiency calculated from the simulation model showed a maximum relative deviation of 1.21 when compared with the steam generator efficiency of the PECEM power plant.

Table 3. Operation maneuvers to assure best-operating conditions

| | **P2=85°C and P5=1.5%** | | | **P2=75°C and P5=1.5%** | |
|---|---|---|---|---|---|
| | Lower limit | Upper limit | | Lower limit | Upper limit |
| P1 | 24 | 26 | P1 | 24 | 25 |
| P4 | 0.8 | 0.95 | P4 | 0.8 | 0.9 |
| P6 | 18 | 23 | P6 | 18 | 23 |
| P7 | 70 | 85 | P7 | 70 | 85 |
| | **P2=80°C and P5=1.5%** | | | **P2=80°C and P5=2%** | |
| | Lower limit | Upper limit | | Lower limit | Upper limit |
| P1 | 24 | 28 | P1 | 24 | |
| P4 | 0.8 | 0.95 | P4 | 0.8 | |
| P6 | 18 | 23 | P6 | 23 | |
| P7 | 70 | 85 | P7 | 70 | 85 |

The experiments performed through the DoE were used to to build a second-order polynomial model according to the RSM. The results is a algebraic expression (Equation 1) capable of representing the steam generator behavior and suit as a surrogate model of the original system. The equation displayed an adjusted $R^2$ of 99.98% and a predicted $R^2$ of 99.95%. The model validation varied the factors randomly to represent twenty new operational conditions besides the reproduction of the 54 initial experiments. The maximum relative deviation was found to be 0.0172. The factors were ranked based on their order of importance, where the first one has the higher impact. The most important factors were the pulverized coal outlet temperature (P2) and the excess $O_2$ (P5).

The use of surrogate models helps in drastically reducing the modeling time or experimentation hard to perform. The significant variables become decision variables to the operator. The surrogate model defined using RSM and DoE set the best-operating conditions and propose operation maneuvers to improve performance. The results add objectivity to the decision-making process during operation, reduces variability and improves quality assuring a standardized operation.

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# 8 APPENDIX

## 8.1 Simulation Model Results

Table 4. Steam generator efficiency (S1) calculated with the simulation model according to a DoE planning

| | **Factors (controllable parameters)** | | | | | | **Response** |
|---|---|---|---|---|---|---|---|
| Experiment number | P1 | P2 | P4.B | P5 | P6 | P7 | S1 |
| 1 | 28.0 | 75 | 0.80 | 2.3 | 21 | 85 | 83.42 |
| 2 | 28.0 | 85 | 0.88 | 3.0 | 21 | 78 | 82.65 |
| 3 | 28.0 | 65 | 0.88 | 3.0 | 21 | 78 | 80.97 |
| 4 | 28.0 | 65 | 0.88 | 1.5 | 21 | 78 | 82.38 |
| 5 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 6 | 26.0 | 85 | 0.88 | 2.3 | 23 | 85 | 83.42 |
| 7 | 26.0 | 75 | 0.80 | 1.5 | 21 | 85 | 84.15 |
| 8 | 26.0 | 85 | 0.80 | 2.3 | 23 | 78 | 83.56 |
| 9 | 26.0 | 75 | 0.95 | 1.5 | 21 | 85 | 83.94 |
| 10 | 26.0 | 65 | 0.95 | 2.3 | 18 | 78 | 81.71 |
| 11 | 28.0 | 75 | 0.88 | 3.0 | 18 | 78 | 82.52 |
| 12 | 24.0 | 75 | 0.80 | 2.3 | 21 | 70 | 83.55 |
| 13 | 26.0 | 65 | 0.88 | 2.3 | 23 | 85 | 81.77 |
| 14 | 28.0 | 75 | 0.95 | 2.3 | 21 | 85 | 83.18 |
| 15 | 24.0 | 75 | 0.95 | 2.3 | 21 | 70 | 83.34 |
| 16 | 26.0 | 85 | 0.80 | 2.3 | 18 | 78 | 83.55 |
| 17 | 26.0 | 75 | 0.95 | 3.0 | 21 | 85 | 82.55 |
| 18 | 26.0 | 75 | 0.95 | 1.5 | 21 | 70 | 83.94 |
| 19 | 28.0 | 75 | 0.95 | 2.3 | 21 | 70 | 83.18 |
| 20 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 21 | 24.0 | 75 | 0.88 | 1.5 | 18 | 78 | 84.06 |
| 22 | 24.0 | 75 | 0.88 | 3.0 | 18 | 78 | 82.71 |
| 23 | 24.0 | 85 | 0.88 | 1.5 | 21 | 78 | 84.06 |
| 24 | 26.0 | 75 | 0.80 | 3.0 | 21 | 85 | 82.78 |
| 25 | 24.0 | 75 | 0.88 | 3.0 | 23 | 78 | 82.71 |
| 26 | 26.0 | 85 | 0.95 | 2.3 | 18 | 78 | 83.35 |
| 27 | 24.0 | 85 | 0.88 | 3.0 | 21 | 78 | 82.71 |
| 28 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 29 | 26.0 | 65 | 0.80 | 2.3 | 18 | 78 | 81.91 |
| 30 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 31 | 26.0 | 85 | 0.88 | 2.3 | 18 | 70 | 83.41 |
| 32 | 26.0 | 85 | 0.88 | 2.3 | 18 | 85 | 83.41 |
| 33 | 24.0 | 65 | 0.88 | 1.5 | 21 | 78 | 83.98 |
| 34 | 28.0 | 75 | 0.88 | 1.5 | 23 | 78 | 83.95 |
| 35 | 24.0 | 65 | 0.88 | 3.0 | 21 | 78 | 82.62 |
| 36 | 24.0 | 75 | 0.80 | 2.3 | 21 | 85 | 83.55 |
| 37 | 26.0 | 65 | 0.88 | 2.3 | 18 | 70 | 81.77 |
| 38 | 26.0 | 85 | 0.88 | 2.3 | 23 | 70 | 83.42 |
| 39 | 26.0 | 65 | 0.88 | 2.3 | 23 | 70 | 81.77 |
| 40 | 26.0 | 75 | 0.80 | 3.0 | 21 | 70 | 82.78 |
| 41 | 26.0 | 65 | 0.95 | 2.3 | 23 | 78 | 81.71 |
| 42 | 26.0 | 65 | 0.88 | 2.3 | 18 | 85 | 81.77 |
| 43 | 28.0 | 75 | 0.88 | 1.5 | 18 | 78 | 83.95 |
| 44 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 45 | 26.0 | 65 | 0.80 | 2.3 | 23 | 78 | 81.92 |
| 46 | 28.0 | 75 | 0.88 | 3.0 | 23 | 78 | 82.52 |
| 47 | 24.0 | 75 | 0.88 | 1.5 | 23 | 78 | 84.07 |
| 48 | 28.0 | 75 | 0.80 | 2.3 | 21 | 70 | 83.42 |
| 49 | 28.0 | 85 | 0.88 | 1.5 | 21 | 78 | 84.06 |
| 50 | 26.0 | 75 | 0.80 | 1.5 | 21 | 70 | 84.15 |
| 51 | 26.0 | 85 | 0.95 | 2.3 | 23 | 78 | 83.35 |
| 52 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 |
| 53 | 24.0 | 75 | 0.95 | 2.3 | 21 | 85 | 83.34 |
| 54 | 26.0 | 75 | 0.95 | 3.0 | 21 | 70 | 82.55 |

# 9 Surrogate model validation

Table 5. Execution of the experiments through the simulation model

| | **Factors (controllable parameters)** | | | | | | **Response S1** | |
|---|---|---|---|---|---|---|---|---|
| Experiment number | P1 | P2 | P4.B | P5 | P6 | P7 | Simulation model | Surrogate model |
| 1 | 28.0 | 75 | 0.80 | 2.3 | 21 | 85 | 83.42 | 83.43 |
| 2 | 28.0 | 85 | 0.88 | 3.0 | 21 | 78 | 82.65 | 82.57 |
| 3 | 28.0 | 65 | 0.88 | 3.0 | 21 | 78 | 80.97 | 80.94 |
| 4 | 28.0 | 65 | 0.88 | 1.5 | 21 | 78 | 82.38 | 82.36 |
| 5 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 6 | 26.0 | 85 | 0.88 | 2.3 | 23 | 85 | 83.42 | 83.41 |
| 7 | 26.0 | 75 | 0.80 | 1.5 | 21 | 85 | 84.15 | 84.16 |
| 8 | 26.0 | 85 | 0.80 | 2.3 | 23 | 78 | 83.56 | 83.56 |
| 9 | 26.0 | 75 | 0.95 | 1.5 | 21 | 85 | 83.94 | 83.94 |
| 10 | 26.0 | 65 | 0.95 | 2.3 | 18 | 78 | 81.71 | 81.71 |
| 11 | 28.0 | 75 | 0.88 | 3.0 | 18 | 78 | 82.52 | 82.53 |
| 12 | 24.0 | 75 | 0.80 | 2.3 | 21 | 70 | 83.55 | 83.54 |
| 13 | 26.0 | 65 | 0.88 | 2.3 | 23 | 85 | 81.77 | 81.78 |
| 14 | 28.0 | 75 | 0.95 | 2.3 | 21 | 85 | 83.18 | 83.19 |
| 15 | 24.0 | 75 | 0.95 | 2.3 | 21 | 70 | 83.34 | 83.34 |
| 16 | 26.0 | 85 | 0.80 | 2.3 | 18 | 78 | 83.55 | 83.56 |
| 17 | 26.0 | 75 | 0.95 | 3.0 | 21 | 85 | 82.55 | 82.55 |
| 18 | 26.0 | 75 | 0.95 | 1.5 | 21 | 70 | 83.94 | 83.94 |
| 19 | 28.0 | 75 | 0.95 | 2.3 | 21 | 70 | 83.18 | 83.19 |
| 20 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 21 | 24.0 | 75 | 0.88 | 1.5 | 18 | 78 | 84.06 | 84.05 |
| 22 | 24.0 | 75 | 0.88 | 3.0 | 18 | 78 | 82.71 | 82.70 |
| 23 | 24.0 | 85 | 0.88 | 1.5 | 21 | 78 | 84.06 | 84.09 |
| 24 | 26.0 | 75 | 0.80 | 3.0 | 21 | 85 | 82.78 | 82.77 |
| 25 | 24.0 | 75 | 0.88 | 3.0 | 23 | 78 | 82.71 | 82.71 |
| 26 | 26.0 | 85 | 0.95 | 2.3 | 18 | 78 | 83.35 | 83.34 |
| 27 | 24.0 | 85 | 0.88 | 3.0 | 21 | 78 | 82.71 | 82.74 |
| 28 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 29 | 26.0 | 65 | 0.80 | 2.3 | 18 | 78 | 81.91 | 81.93 |
| 30 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 31 | 26.0 | 85 | 0.88 | 2.3 | 18 | 70 | 83.41 | 83.41 |
| 32 | 26.0 | 85 | 0.88 | 2.3 | 18 | 85 | 83.41 | 83.41 |
| 33 | 24.0 | 65 | 0.88 | 1.5 | 21 | 78 | 83.98 | 82.46 |
| 34 | 28.0 | 75 | 0.88 | 1.5 | 23 | 78 | 83.95 | 83.96 |
| 35 | 24.0 | 65 | 0.88 | 3.0 | 21 | 78 | 82.62 | 81.11 |
| 36 | 24.0 | 75 | 0.80 | 2.3 | 21 | 85 | 83.55 | 83.54 |
| 37 | 26.0 | 65 | 0.88 | 2.3 | 18 | 70 | 81.77 | 81.78 |
| 38 | 26.0 | 85 | 0.88 | 2.3 | 23 | 70 | 83.42 | 83.41 |
| 39 | 26.0 | 65 | 0.88 | 2.3 | 23 | 70 | 81.77 | 81.78 |
| 40 | 26.0 | 75 | 0.80 | 3.0 | 21 | 70 | 82.78 | 82.77 |
| 41 | 26.0 | 65 | 0.95 | 2.3 | 23 | 78 | 81.71 | 81.71 |
| 42 | 26.0 | 65 | 0.88 | 2.3 | 18 | 85 | 81.77 | 81.78 |
| 43 | 28.0 | 75 | 0.88 | 1.5 | 18 | 78 | 83.95 | 83.95 |
| 44 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 45 | 26.0 | 65 | 0.80 | 2.3 | 23 | 78 | 81.92 | 81.93 |
| 46 | 28.0 | 75 | 0.88 | 3.0 | 23 | 78 | 82.52 | 82.54 |
| 47 | 24.0 | 75 | 0.88 | 1.5 | 23 | 78 | 84.07 | 84.06 |
| 48 | 28.0 | 75 | 0.80 | 2.3 | 21 | 70 | 83.42 | 83.43 |
| 49 | 28.0 | 85 | 0.88 | 1.5 | 21 | 78 | 84.06 | 83.99 |
| 50 | 26.0 | 75 | 0.80 | 1.5 | 21 | 70 | 84.15 | 84.16 |
| 51 | 26.0 | 85 | 0.95 | 2.3 | 23 | 78 | 83.35 | 83.34 |
| 52 | 26.0 | 75 | 0.88 | 2.3 | 21 | 78 | 83.33 | 83.33 |
| 53 | 24.0 | 75 | 0.95 | 2.3 | 21 | 85 | 83.34 | 83.34 |
| 54 | 26.0 | 75 | 0.95 | 3.0 | 21 | 70 | 82.55 | 82.56 |

Table 6. Relative deviation of the simulation model and the surrogate model for 20 new operating conditions

| **Test** | **P1** | **P2** | **P4** | **P5** | **P6** | **P7** | **Simulation Model** | **Surrogate Model** | **Relative Deviation** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 26.0 | 75 | 0.80 | 2.3 | 21 | 85 | 83.48 | 83.49 | -0.0002 |
| 2 | 26.5 | 76 | 0.82 | 2.4 | 21 | 83 | 83.33 | 83.40 | -0.0008 |
| 3 | 27.0 | 77 | 0.84 | 2.5 | 22 | 81 | 83.19 | 83.30 | -0.0013 |
| 4 | 27.5 | 78 | 0.86 | 2.6 | 22 | 79 | 83.05 | 83.20 | -0.0017 |
| 5 | 24.5 | 67 | 0.90 | 1.7 | 19 | 75 | 83.77 | 82.70 | 0.0128 |
| 6 | 25.0 | 68 | 0.92 | 1.8 | 20 | 77 | 83.66 | 82.77 | 0.0105 |
| 7 | 25.5 | 69 | 0.94 | 1.9 | 20 | 79 | 83.54 | 82.84 | 0.0083 |
| 8 | 26.0 | 70 | 0.95 | 2.0 | 21 | 81 | 83.42 | 82.90 | 0.0063 |
| 9 | 26.5 | 71 | 0.90 | 2.1 | 21 | 83 | 83.36 | 82.98 | 0.0046 |
| 10 | 24.5 | 65 | 0.80 | 1.6 | 18 | 70 | 83.99 | 82.54 | 0.0172 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 11 | 25.0 | 66 | 0.82 | 1.7 | 19 | 72 | 83.85 | 82.62 | 0.0147 |
| 12 | 25.5 | 67 | 0.84 | 1.8 | 19 | 74 | 83.71 | 82.68 | 0.0124 |
| 13 | 26.0 | 68 | 0.86 | 1.9 | 20 | 76 | 83.58 | 82.73 | 0.0102 |
| 14 | 26.5 | 69 | 0.88 | 2.0 | 20 | 78 | 83.45 | 82.77 | 0.0081 |
| 15 | 27.0 | 70 | 0.90 | 2.1 | 21 | 80 | 83.33 | 82.80 | 0.0063 |
| 16 | 24.5 | 66 | 0.81 | 1.6 | 18 | 72 | 84.08 | 82.78 | 0.0154 |
| 17 | 25.0 | 69 | 0.82 | 1.6 | 19 | 74 | 83.96 | 83.31 | 0.0078 |
| 18 | 25.5 | 72 | 0.83 | 1.6 | 19 | 76 | 83.95 | 83.70 | 0.0029 |
| 19 | 26.0 | 75 | 0.84 | 1.6 | 20 | 78 | 83.93 | 83.96 | -0.0004 |
| 20 | 26.5 | 78 | 0.85 | 1.6 | 20 | 80 | 83.92 | 84.09 | -0.0020 |