



25<sup>th</sup> ABCM International Congress of Mechanical Engineering  
October 20-25, 2019, Uberlândia, MG, Brazil

## COBEM2019-2408 - COAL-FIRED FURNACE BOILER MODEL: SENSITIVITY ANALYSIS AND RESPONSE SURFACE METHOD ASSESSMENT

**Conrado Ermel**

**Paulo Smith Schneider**

Federal University of Rio Grande do Sul

conradoermel@gmail.com; pss@mecanica.ufrgs.br;

**Rafael Zamprogna**

Energia de Portugal - UTE PECÉM

**Abstract.** *The present work presents a parallel between two evaluation tools: the One Factor at Time (OFaT), and the Response Surface Methodology (RSM) when both are applied to a furnace computational combustion model. The assessed model was based on Hottel's zonal method which is capable of estimating the gas and surface temperatures in the furnace domain. The OFaT assessment was performed in a gas/oil experimental furnace, while the RSM was applied to a coal-fired furnace boiler. Results from both evaluation methods were compared and showed that the OFaT approach was capable of identifying the model non-linearity as well as the influence level of each input factor alone. Inter-relation between the input factors and its combined influence was only perceived by means of RSM. The method also helped to identify a specific input combination that resulted in model convergence-failure. In addition to highlighting the potential of each analysis method, the present work also revealed a unique input configuration where the model did not work properly, confirming the adequacy of RSM to computational modeling evaluation.*

**Keywords:** *Sensitivity Analysis, Response Surface Method, Boiler Modeling, Zonal Method, DoE.*

### List of Symbols

$\overline{g_i g_j}$	Gas - Gas Direct Exchange Area
$\overline{g_i s_j}$	Gas - Surface Direct Exchange Area
$\overline{s_i s_j}$	Surface - Surface Direct Exchange Area
$\tau(r)$	Fraction of transmitted radiant energy
$\theta_j$	Angle Between
$i, j, k$	Zones
$K$	Gas absorption coefficient
$r$	The line connecting the center of two selected zones
DoE	Design of Experiments
LHV	Lower Heating Value
RSM	Response Surface Methodology

## 1. INTRODUCTION

Despite the continuous growth rate of renewable energies, coal-fired steam generators still play an important role in the energy matrix of several countries. However, environmental policies are more restrictive than ever, forcing existent coal-fired power stations to retrofit aiming to improve efficiency and control pollutant emission. In this scenario, computational simulations are a cost-effective approach to study these process and to test new configurations. In addition, computational prediction models have been widely used to support operation (Zhao *et al.*, 2017). Numerical models such as the Zonal Method (Hottel and Cohen, 1958) are especially interesting to solve complex radiative heat transfer exchange in furnaces with participant media, combining resolution to cost-benefit relation, as it displays a relative simplicity in its implementation, allied to the low computational effort. The zonal method was first proposed by McAdams and Hottel (1954) and consists in subdividing the non-isothermal and inhomogeneous furnace domain into isotherm and homogeneous surface and gas-volume zones.

Although processing time of numerical methods such as the zonal method is usually much smaller than the ones required by Computational Fluid Dynamics (CFD) codes, a large number of simulations can easily preclude research project schedule. Hence tools and methodologies to evaluate models behavior are of great interesting. There are several evaluation tools available, and one of the most popular is the One Factor at Time analysis (Montgomery, 1997). Several processes behavior can be defined by observing the output while each input factor is varied individually. However, this approach can only identify the influence of the factors alone, neglecting the interrelation between them. For this reason, other evaluation procedures have been developed throughout the past years. The RSM, for instance, is a flexible methodology capable of determining the influence of a specific input factor individually, as is can observe the influence of multiple factors combined. In experimental researches, the RSM can be used to explore the parameters influence or to obtain regression models, as developed by Li *et al.* (2019), which studied the NO removal process by using sodium persulfate/limestone slurry. In the work of Ben Khalifa *et al.* (2019), the RSM was also used to assess the role of the input parameters in the chromium removal by adsorption on low-cost biosorbent. Mineral equipment research has also been studied by means of RSM as presented in Nienaber and Auret (2019).

Despite the spread usage of RSM in several research fields, as mentioned earlier, the direct application of RSM to numerical combustion model is not a frequent approach. This paper presents an assessment of how the zonal method behaves concerning changes in some selected input parameters. Two approaches were adopted. At first, an OFaT analysis was carried out, aiming to understand the influence of each input factor in the model. Later, a DoE (Design of Experiments) and RSM (Response Surface Methodology) was employed to study the interrelation between the input factors. A parallel between both evaluation tools is presented as well.

## 2. MATHEMATICAL FORMULATION

The zonal method is based on the calculation of the Direct Exchange Areas (DEA), that relate all zones in the domain, and represent the fraction of radiant energy that leaves a given zone and directly reaches other given ones, as a function of their geometry and the medium radiant characteristics. DEA can be determined by utilizing the following relations (Hottel and Sarofim, 1967):

$$\overline{s_i s_j} = \int_{A_i} \int_{A_j} \tau(r) \frac{\cos \theta_i \cos \theta_j}{\pi r^2} dA_j dA_i, \quad (1)$$

$$\overline{g_i s_j} = \int_{V_i} \int_{A_j} \frac{\tau(r) K_i \cos \theta_j}{\pi r^2} dA_j dV_i, \quad (2)$$

$$\overline{g_i g_j} = \int_{V_i} \int_{V_j} \frac{\tau(r) K_i}{\pi r^2} dV_j dV_i. \quad (3)$$

Term  $\tau(r)$  is the fraction of radiant energy that is transmitted, described as  $\tau(r) = \exp^{-\int_0^r K dr}$ , with  $r$  the straight line that connects the center of two selected zones, and  $\cos \theta_i$  and  $\cos \theta_j$  the angles between  $r$  and the respective normal direction of zones  $i$  and  $j$ , and  $K_i$  is the gas absorption coefficient<sup>1</sup>. Equation 1 indicates the DEA between two surface zones, Eq. 2 the exchange between a surface zone and a gas-volume zone and Eq. (3) the exchange between two gas-volume zones. The DEA were determined by the polynomial correlations proposed by Tucker (1986). The simultaneous effect of the incident radiation coming from all zones, with multiple reflections inside the enclosure, was solved by means of the Total Exchange Area TEA concept, which allows simplifying the solution of the energy balance equations. It was adopted the TEA calculation procedure presented by McAdams and Hottel (1954) and Hottel and Sarofim (1967).

One energy equation was stated for each zone, leading to a closed system of  $N$  equations and unknowns. For a surface

<sup>1</sup>  $K$  stands for the gas absorption coefficient integrated over the entire spectrum.

zone, considering the boundary condition of unknown temperature, the adopted energy balance equation is

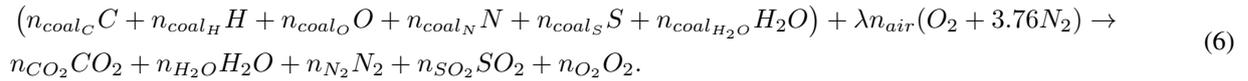
$$\sum_j \overrightarrow{S_j S_i} E_{s,j} + \sum_j \overrightarrow{G_j S_i} E_{g,j} - A_i \epsilon_i E_{s,i} + h_i A_i (T_{g,k} - T_{s,i}) = Q_{net,i}, \quad (4)$$

with  $T_{g,k}$  the adjacent gas-volume temperature. The first and second terms in the left-hand side of the equation stand for the radiation received from other surfaces and gas zones, respectively. The third term represents the emitted radiation. Convection is accounted for by the relation  $h_i A_i (T_{g,k} - T_{s,i})$ , and the energy through the surface is represented by  $Q_{net,i}$ . The gas-volume zone balance requires a different energy equation, stated as

$$\sum_j \overrightarrow{G_j G_i} E_{g,j} + \sum_j \overrightarrow{S_j G_i} E_{s,j} - \sum_j 4a_{g,n} K_n V_i E_{g,i} + Q_{e,i} = Q_{u,g_i} - Q_{c,i}, \quad (5)$$

that comprehends the radiant heat received from all surface and gas zones (first and second terms in the left-hand side of the equation) and the radiation emitted to them, represented by the third term. Additionally, three terms of energy source/sink are included: the energy rate release by combustion  $Q_{c,i}$ , the transient term  $Q_{u,g_i}$ , and the rate of change in the sensible enthalpy of a gas between the control volume inlet and outlet, plus the convection from any surface adjacent to the gas-volume  $Q_{e,i}$ . Gas-volumes are modeled as Perfect Stirred Reactors (PSR). The energy released in the combustion process was estimated by the coal LHV and its mass flow rate.

The combustion process was modeled by atom balance, for each of the gas volumes, by considering complete combustion as



Although being an important matter in coal combustion, no soot formation/oxidation model was implemented. The  $NO$  formation model was adapted from Zhao *et al.* (2017), where Equation 7 represents the Zeldovich mechanism

$$\frac{\partial R_{NO-thermal}}{\partial t} = 3.6 \times 10^{11} \exp\left(\frac{-38370}{T_{fg}}\right) C_{N_2} C_O \quad (7)$$

with  $T_{fg}$  being the furnace homogeneous temperature,  $C_{N_2}$  the nitrogen concentration in molar basis, and  $C_O$  the O-radical mole fraction, defined as:

$$C_O \approx 12.567 \times 10^3 T_{fg}^{-0.5} \exp\left(\frac{-31096}{T_{fg}}\right) \sqrt{C_{O_2}} \quad (8)$$

with  $C_{O_2}$  the oxygen molar fraction. Regarding the Fuel-NO mechanism, it was assumed that all coal-N is converted into  $HCN$  immediately, and then oxidized into  $NO$  at the rate of Equation 9.

$$\frac{\partial R_{NO-HCN}}{\partial t} = 10^{10} C_{HCN} C_{O_2}^b \exp\left(\frac{-33713}{T_{fg}}\right) \quad (9)$$

Assuming  $b = 0$  for  $C_{O_2} > 0.018$  and  $b = 1$  for  $C_{O_2} < 0.0025$ , according to Hill and Douglas Smoot (2000). Equations 7 and 9 are presented in derivative form, and are integrated over the residence time  $t$  estimated for an imaginary particle.

### 3. SENSITIVITY ANALYSIS: STROM'S FURNACE

The work presented by Ström (1980) was chosen to validate the furnace heat exchange model accuracy and reliability. That author was the first to propose the Imaginary Plane Method (IPM), which is a simplification of the zonal method. Ström has modeled an experimental scale furnace, designed to operate with natural gas and oil, as presented in Figure 1. This furnace conveniently can be described as a composition of several squares and cubes, which leads to a straightforward application of Tucker's DEA correlations (Tucker, 1986). The burner was placed in an isolated wall. All sidewalls are adiabatic (Neumann condition), bottom surfaces were set to at a prescribed temperature (Dirichlet condition) and roof surfaces exchanged heat to the environment (Robin condition) with an overall heat transfer coefficient of  $\bar{U} = 5$  W/(m<sup>2</sup>K). In the original work of Ström (1980) Different absorption coefficients were associated with each chamber, both for gas and oil operation. In the present work, average absorption coefficients were adopted for gas and oil ( $\bar{K}_{gas} = 0.26$ ;  $\bar{K}_{oil} = 0.46$ ), based on Ström's original values. Additionally, a gas specific heat of 1.674 kJ/(kg K) was adopted, and the ambient temperature was set to  $T_{amb} = 303$  K. The fuel inlet temperature was  $T_{gas,inlet} = 1550$  K. Emissivities, combustion energy release, and other boundary conditions reproduced from Ström's work are shown in Table 1. No details about the fluid exit plane were available, so it was assumed a free outlet, without any heat exchanger or tube wall,

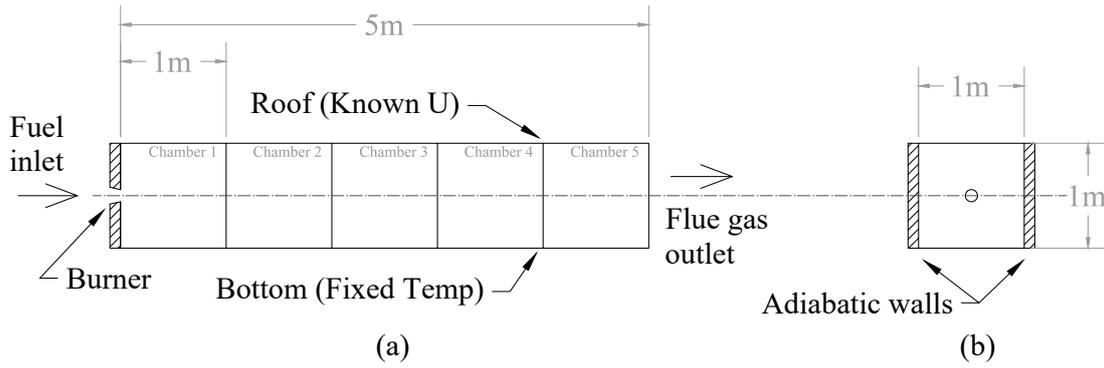


Figure 1. Ström furnace geometry and boundary conditions. a) Right and b) Front views.

Table 1. Input parameters adopted to simulate Ström's furnace (Ström, 1980).

Location	$K_{gas}$ ( $m^{-1}$ )	$K_{oil}$ ( $m^{-1}$ )	$\epsilon$	Temp. (K)	$\bar{U}$ ( $W/(m^2K)$ )	$Q_{comb}$ (kW)
Zone 23 <sup>2</sup>	0.3	0.8	-	-	-	500 <sup>1</sup>
Zone 24 <sup>2</sup>	0.2	0.6	-	-	-	500 <sup>1</sup>
Zone 25 <sup>2</sup>	0.2	0.3	-	-	-	0
Zone 26 <sup>2</sup>	0.3	0.3	-	-	-	0
Zone 27 <sup>2</sup>	0.3	0.3	-	-	-	0
Roof	-	-	0.5	-	5	-
Floor	-	-	0.87	1798	-	-
Inlet wall	-	-	0.5	-	-	-
Outlet wall	-	-	1	-	-	-

<sup>1</sup> Ström (1980) considered a fixed combustion energy released only in the two first chambers;

<sup>2</sup> The simulations were performed considering averaged absorption coefficients for all gas zones ( $\bar{K}_{gas} = 0.26$ ;  $\bar{K}_{oil} = 0.46$ );

modeled as a near black body plane at  $T_{amb}$ , with  $\epsilon_{outlet} = 0.99$ , as adopted by Díez *et al.* (2005). For the convection heat transfer coefficient a reference value of  $1 W/(m^2K)$  was adopted after Ström (1980).

The model sensitivity in respect to input and process parameters was assessed by means of a One-Factor-at-a-Time (OFaT) approach. The procedure consists of establishing a set of baseline levels for all the chosen input factors, followed by swiping each one of them at a time throughout its range, while the remaining factors are kept at their baseline level (Montgomery, 1997). Five selected parameters were assessed, namely: fuel and air mass flow rates, convection heat transfer coefficient, inlet gas temperature, gas absorption coefficient, and wall emissivity. Baseline values for these parameters, also called factors, are presented in Table 2. Fuel type was not assessed at this point, because its influence was already embedded on some of the former factors. Ten different values were simulated within each factor range. Figure 2 presents

Table 2. OFaT baseline factor values and correspondent ranges.

Factor	Base-Value	Range	Unit
Mass flow rate - $\dot{m}$	0.3842	$1e^{-20}$ - 0.3842	kg/s
Convective coefficient - $h_{conv}$	1	0.5 - 100	$W/(m^2K)$
Gas inlet temperature - $T_{gas,inlet}$	1550	1000 - 2000	K
Absorption coefficient - $K$	0.5	0.1 - 0.9	-
Wall emissivity - $\epsilon_w$	0.5	0.1 - 0.95	-

the sensitivity analysis results for the temperature  $T_2$ , which is the first surface zone in the geometry roof. Following, the sensitivity analysis was performed for the gas temperature,  $T_{27}$ , the last gas volume (chamber) in the furnace. The same factors of the previous analysis were evaluated, over the same range, and the results are presented in Fig. 3.

### 3.1 Discussion on the Sensitivity Analysis Results

The first sensitivity result concerns to zone 2 temperature (Figure 2), where flat horizontal lines indicate the small influence of this factor on the model output. Air mass flow rate and fuel did not generate any changes in zone 2 temperature. Although this result seems to be unexpected, it is reasonable according to the Ström's experiment, which held a

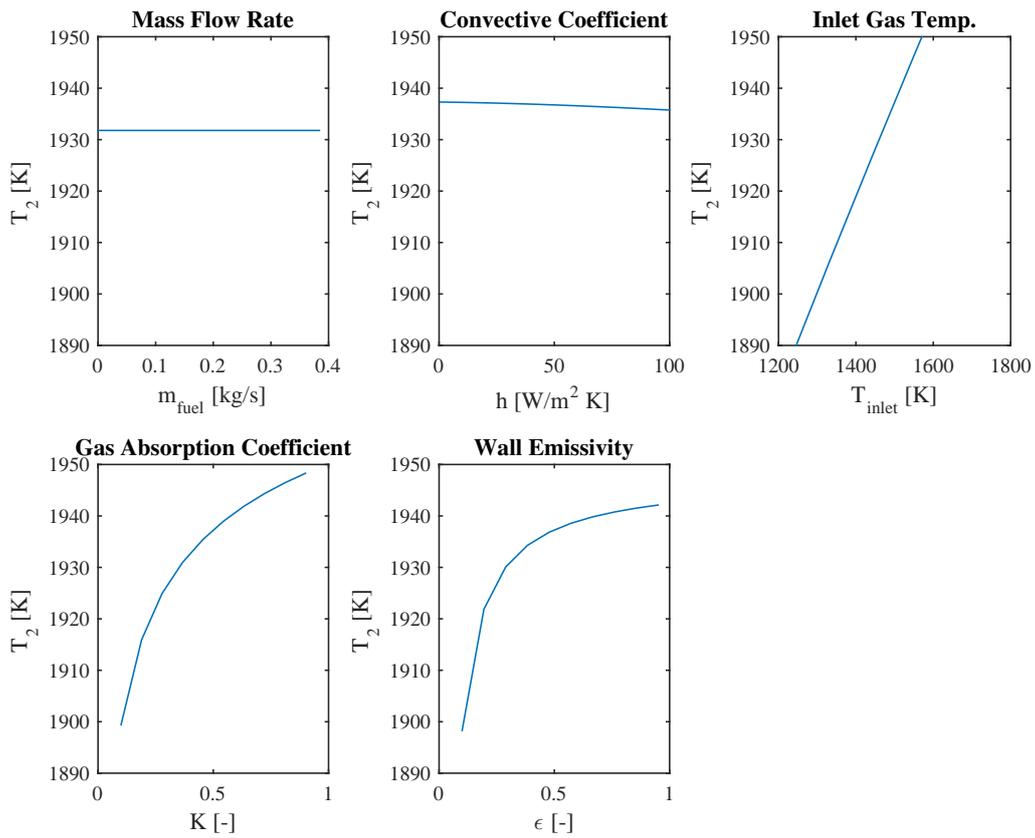


Figure 2. Sensitivity analysis for Ström's furnace simulation. Results for the temperature of first chamber roof,  $T_2$ .

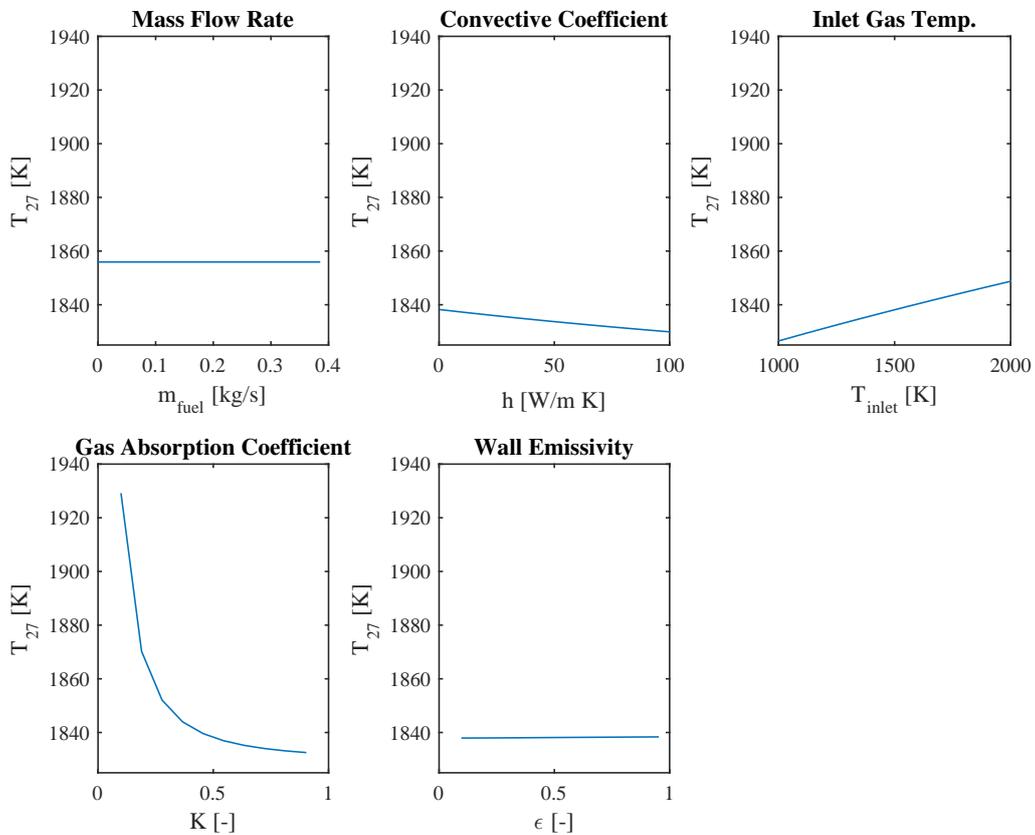


Figure 3. Sensitivity analysis for Ström's furnace simulation. Results for the temperature of the last gas chamber  $T_{27}$ .

fixed combustion heat release of 500 kW in gas zones 23 and 24. Changes in the convection heat transfer coefficient also presented small influence in  $T_2$ . Though convection plays a minor role compared to radiation inside the boiler, physical behavior occurs as expected, i.e. higher coefficient means higher convective heat transfer and consequently, lower roof surface temperature. Ström's furnace operates with fuel and air inlet temperature of  $T_{gas,inlet} = 1550$  K, which directly influences the temperature of zone 2. That impact, although significant, cannot be overestimated, based on physical and practical limits of real furnace preheating systems. Gas absorption coefficient and wall emissivities forced  $T_2$  to behave in a non-linear way and with a similar output trend. The span of the factors within their range resulted in  $T_2$  changes up to 2.63 % for gas absorption coefficient and 2.1 % for wall emissivity. Gas absorption coefficient directly impacts the direct exchange areas and consequently, the energy balances. The higher is the  $K$  value, lower will be the gas absorption allowing the increase of the radiative heat exchange. The roof temperature tends to rise along, as observed in Figure 2. Concerning the wall emissivity, the model behavior is straightforward inferred, once higher emissivities mean the intensification of the radiative heat transfer, raising the surface temperature. Results for temperature  $T_{27}$  were significantly distinct from the ones presented in Figure 2, except for mass flow rate and the convective heat transfer coefficient, which conserved a similar behavior. The inlet gas temperature, although keeping the tendency to increase  $T_{27}$ , displayed smaller influence in that case. Wall emissivities seem to have no impact in  $T_{27}$  since it remained almost constant over the entire range of  $\epsilon$ . Perhaps the most interesting result in this second sensitivity analysis lied on the behavior of  $T_{27}$  as a function of the gas absorption coefficient. With decreasing  $K$ , the gas transmissivity,  $\tau(r) = \exp^{-\int_0^r K dr}$ , decreased as well and the emitted and absorbed radiation in Equation 5 led the gas temperature to decrease, also in a non-linear way. Gas absorption coefficient generated changes of 5.46 % in the gas temperature of the last chamber,  $T_{27}$ . The sensitivity analysis indicates that the gas absorption coefficient and wall emissivities are the most relevant parameters in the model.

Interesting differences can be observed when results of zone 2, the roof surface, are compared to the ones of gas zone 27. Gas absorption coefficient presents an inverse behavior, which is a reasonable result. A higher value of  $K$  enhances the gas capacity of absorbing and emit radiation. As the heat exchange is augmented by the  $K$ , the temperature of the surface zones closer to the furnace burner also tends to increase. This radiation intensification also leads to a flue gas with lower energy in the gas volume zones, which results in lower temperatures, as shown in Fig. 3.

#### 4. RSM - RESPONSE SURFACE METHODOLOGY

The inter-dependence between the input factor ranges at different levels and understanding of how their combination can affect the output, could not be achieved by the sensitivity analysis alone, so another approach was also required. The Design of Experiments (DoE) can provide several procedures to assess simulated or experimental data, and is a suitable tool to identify the coupled sensitivity of multi-input factors on the model output. Among the known techniques, the Box-Behnken method with central composition generates a smaller number of combinations when compared to regular  $3^k$  factorial design (Ferreira *et al.*, 2007). This technique, however, demands that whenever some factor is at its maximum value, no other factor be at its maximum value too. An alternative to that restriction is the Response Surface Methodology (RSM) (Montgomery, 1997). The RSM allows assessing several input factors simultaneously, generating a visual report of factor dependence.

In the present work, the RSM was employed to assess a zonal-method-based boiler model, Eq. (1) to Eq. (5). Equations were solved in a MATLAB (The MathWorks, 2012) code to account for the DEA and TEA, while an EES (F-Chart Software, 2019) subroutine was used to solve the energy equation system. Contour plots and surface curves were generated in Minitab 18.1. Differently from the model evaluated with the sensitivity analysis, which considered a fixed combustion-heat-release regardless of the fuel and airflow rates, in the RSM analysis, the model used Eq. (6) to predict the chemical species in the flue gas, while the coal LHV (Lower Heating Value) was associated with the coal mass flow rate to estimate the energy introduced in the furnace. Real operational data from the coal-fired power plant of PECÉM, located in Ceará, Brazil were introduced in the geometry presented in Fig. 4.

The operational data was obtained by taking into consideration the trend in Figure 5, which presents the power station operation regime along an entire year. The boiler operates under two well-defined regimes, as it generates 240 MW when operating in low load condition, or it generates its maximum power output of 360 MW. Intermediary measures represent transient operation between the two power levels. This operational behavior is due to the coal feed system, and the coal grinding mills limitations. Therefore, the 360 MW full power operation condition was chosen as the standard for the RSM evaluation. The simulation was performed adopting the data displayed in Table 3 which are the original operational data from PECÉM. Simulating the operation with these process parameters was intentional, even though the model geometry is much smaller than the real furnace domain. This strategy was adopted to assess model behavior instead of reaching PECÉM boiler output results. Three input factors were selected, namely, Flow rate factor, Gas absorption coefficient, and Wall emissivity. The factors were ranged as presented in Tab. 4. At first, the wall emissivity was set from 0.1 to 0.95. However the RSM helped to identify that for the following input combination: Flow rate factor = 0.5, Absorption coefficient = 0.1 and Wall emissivity = 0.1, convergence was not reached. Deeper analysis showed that this combination generated inconsistencies in the energy-balance equation solver block, in the EES code. Although these input values were far from actual operation condition, considering that  $\epsilon$  will most likely be closer to 1 (Lowe *et al.*, 1975; Lockwood *et al.*,

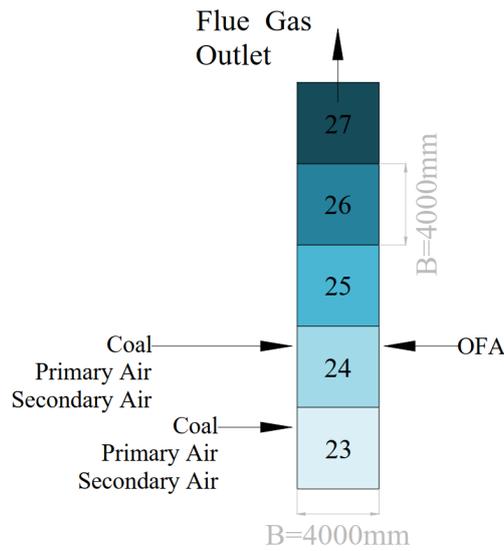


Figure 4. Geometry used in the RSM analysis.

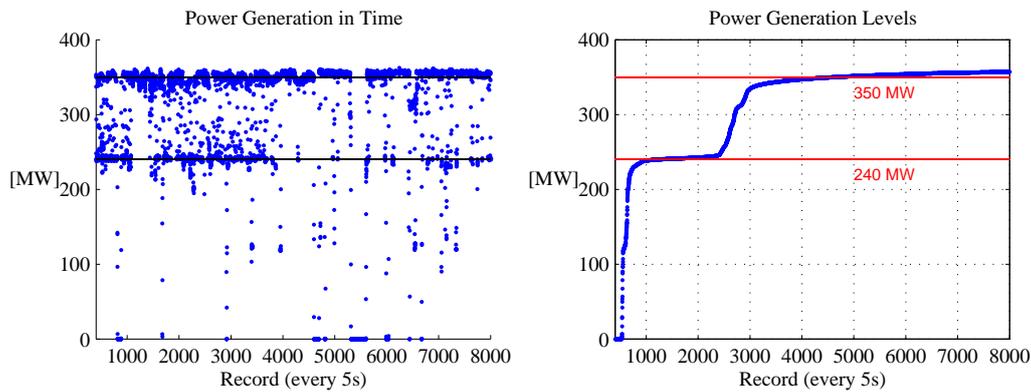


Figure 5. Power generation trend (one-year operation). The *Power Generation in Time* graphic shows the control system records. The *Power Generation Levels* graphic represents the system records, in ascending order, to emphasize the two levels of generation: 240 MW and 360 MW.

Table 3. Power plant process parameters and boundary conditions.

Parameter	Value	Unit
Coal flow rate	36.89	kg/s
Primary air flow rate	74.56	kg/s
Secondary air flow rate	238.28	kg/s
Over fire air flow rate	43.92	kg/s
Inlet coal/air temperature	623	K
Absorption coefficient	0.5	$m^{-1}$
Wall emissivity	0.5	-
Wall temperature (zone: 2 to 21)	686	K

1980; Carvalho and Farias, 1998; Chen *et al.*, 2017), that model limitation could not be predicted by running a simple parametric sensitivity analysis. To overcome this problem the ranges presented in Tab. 4 were adopted.

Figure 6 (a) presents the contour plot of the temperature of zone 27,  $T_{27}$ , as a function of the wall emissivity and the flow rate. In Fig. 6 (b) the surface curve is presented. The second analysis considered the inter-relation between the flow rate and the gas absorption coefficient. The contour result and the surface are presented in Fig. 7(a) and (b), respectively. The combined influence of wall emissivity and the gas absorption coefficient, last analysis, is presented in Fig. 8(a) for the contour map, as the surface response is shown in Fig. 8(b).

Table 4. Input factors used in the RSM evaluation.

Input factor <sup>1</sup>	Description	Minimum	Maximum
Flow	Coal and air inlet fraction	0.5	1.5
Emiss	Wall emissivities	<b>0.3</b>	0.95
Abs	Gas absorption coefficient	0.1	1

<sup>1</sup> Flow = 1 is the design mass flow rate for a 360 MW electric output operation;

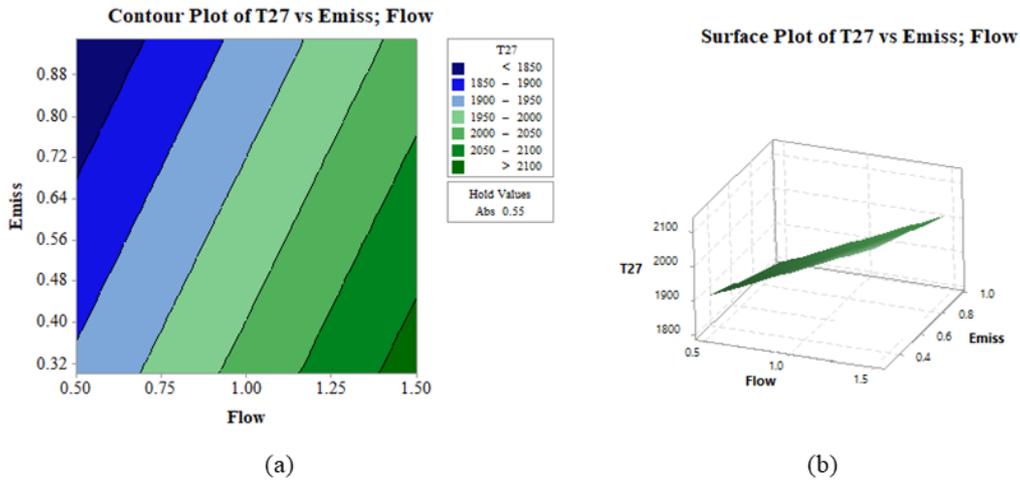


Figure 6. Response Surface Method: Flow rate and wall emissivity presented a linear inter-relation.

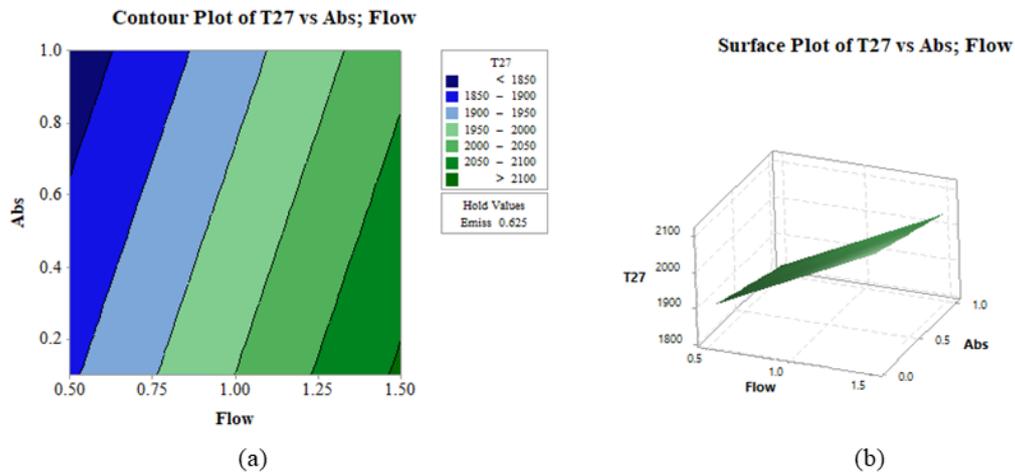


Figure 7. Response Surface Method: Flow rate and gas absorption coefficient presented a linear inter-relation.

#### 4.1 Discussion on the RSM Results

Results suggest that the combination of the walls emissivities and the flow rate generates a linear relation in  $T_{27}$ . Wall emissivity has an inverse influence on the gas temperature in the furnace. Higher emissivities generate the intensification of the radiative heat transfer, so the gas temperature decreases in zone 27. Besides,  $T_{27}$  is directly proportional to the Coal and air flow rate. The combined effect of the flow rate and the absorption coefficient on the temperature of zone 27 is presented in Fig. 7. The same linear trend was observed, however, with a slightly different slope.

A non-linear trend was observed for the absorption coefficient and wall emissivity response curve, displayed in Fig. 8. It can be observed that  $T_{27}$  responds to the variation of both input factors, however, it does not follow a linear relation. When both emissivity and absorption coefficient is close to their minimum,  $T_{27}$  remains at an intermediary value. For the opposite condition (both factors at their maximum values),  $T_{27}$  assumes its lower value, revealing the interdependence existing in the studied model.

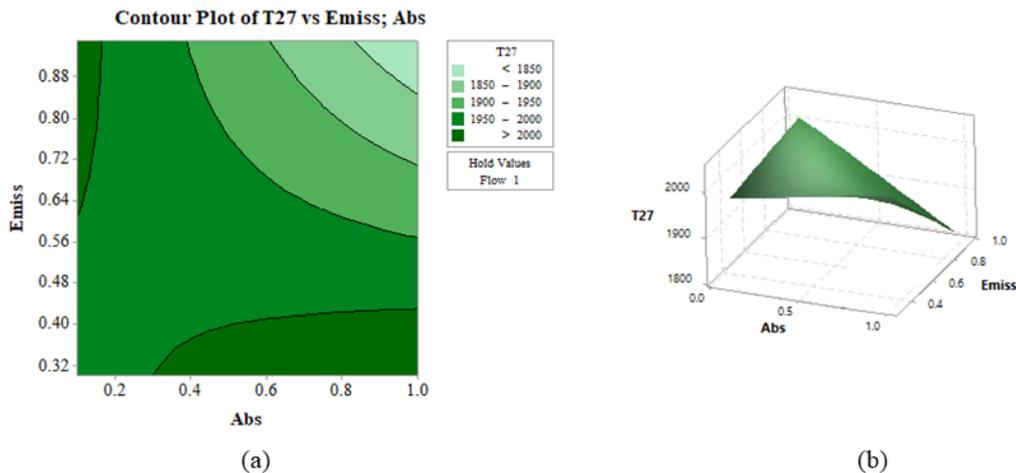


Figure 8. Response Surface Method: Gas absorption coefficient and wall emissivity presented a non-linear inter-relation.

## 5. CONCLUSIONS

The sensitivity analysis allows understanding how the model responds to changes in some selected input factor. Once the procedure consists in setting each parameter at a time, the only effect that can be observed is the ones caused by the factor alone, i.e. no relation between the factors can be evaluated in this approach. The sensitivity analysis revealed that among the five evaluated parameters, gas absorption coefficient generates the most significant influence in temperatures  $T_2$  and  $T_{27}$ . Although the changes in those temperatures, related to the inlet gas temperature, are considerable high, they can not be overestimated since this factor is limited by physical constraints. Sensitivity analysis also confirmed an expected result concerning the convection. As affirmed by different authors, radiation is the most important heat transfer mechanism in coal-fired boilers furnaces, therefore, the convective coefficient has no great impact on neither  $T_2$  or  $T_{27}$ .

The second assessment approach, the response surface method, helped to unveil the interrelation between the input factors. The RSM tool proved itself as a handy tool to analyze the model behavior and the sensitivity to changes in the input factors. The presented contour plots and surface plots displayed not only the direct effect of each factor in  $T_2$  or  $T_{27}$ , but also the model behavior as a function of the combined factors varying simultaneously.

Sensitivity analysis, or OFaT, has been used to evaluate phenomena trends as well as mathematical models behavior. Especially in the field of computational modeling, this tool can be of great interest in the understanding of how the model outputs respond to changes in the input parameters. Despite its usefulness, the OFaT has some important limitations, since it does not consider the relationship between the input factors. On the other hand, the RSM, based on DoE strategies has the capability of capturing the combined effect of input factors. In the present work, this capability can be observed as the RSM assessment reveal a non-linear relation for the absorption coefficient and wall emissivity response curve, displayed in Fig. 8. This result particularly denotes the difference between sensitivity analysis and the RSM. From the first one it could be inferred that  $T_{27}$  tends to decrease as *Abs* and *Emiss* grows independently from each other. The RSM, yet, unveils the interrelation surface between wall emissivity and gas absorption coefficient, displaying in which ranges they could result in  $T_{27}$  maximum or minimum values. Figure 8 highlight that maximum gas temperature would only be achieved when one of the factors was set to its maximum, whereas the other is closer to its minimum value. Analysis results indicate that RSM can be a valuable tool to understand computational models trends and limitations.

## 6. ACKNOWLEDGEMENTS

We acknowledge Energy of Portugal EDP for the financial and technical support to this project; Ermel acknowledges the financial support from CNPq for his MSc grant; Schneider acknowledges CNPq for his research grant (PQ 305357/2013-1).

## 7. REFERENCES

- Ben Khalifa, E., Rzig, B., Chakroun, R., Nouagui, H. and Hamrouni, B., 2019. "Application of response surface methodology for chromium removal by adsorption on low-cost biosorbent". *Chemometrics and Intelligent Laboratory Systems*, Vol. 189, pp. 18–26.
- Carvalho, M.G. and Farias, T.L., 1998. "Modelling Of Heat Transfer In Radiating And Combusting Systems". *Trans IChemE*, Vol. 76, pp. 175–184.
- Chen, S., He, B., He, D., Cao, Y., Ding, G., Liu, X., Duan, Z., Zhang, X., Song, J. and Li, X., 2017. "Numerical

- investigations on different tangential arrangements of burners for a 600 MW utility boiler”. *Energy*, Vol. 122, pp. 287–300.
- Díez, L.I., Cortés, C. and Campo, A., 2005. “Modelling of pulverized coal boilers: review and validation of on-line simulation techniques”. *Applied Thermal Engineering*, Vol. 25, No. 10, pp. 1516–1533.
- F-Chart Software, L., 2019. “EES - Engineering Equation Solver”.
- Ferreira, S., Bruns, R., Ferreira, H., Matos, G., David, J., Brandao, G., da Silva, E., Portugal, L., dos Reis, P., Souza, A. and dos Santos, W., 2007. “Box-Behnken design: An alternative for the optimization of analytical methods”. *Analytica Chimica Acta*, Vol. 597, pp. 176–186.
- Hill, S. and Douglas Smoot, L., 2000. “Modeling of nitrogen oxides formation and destruction in combustion systems”. *Progress in Energy and Combustion Science*, Vol. 26, No. 4-6, pp. 417–458.
- Hottel, H.C. and Cohen, E.S., 1958. “Radiant heat exchange in a gas-filled enclosure: Allowance for nonuniformity of gas temperature”. *AIChE Journal*, Vol. 4, No. 1, pp. 3–14.
- Hottel, H.C. and Sarofim, A.F., 1967. *Radiative Transfer*. McGraw-Hill Book Co, 1st edition.
- Li, Y.x., Xu, Q.y., Guo, R.t., Wang, Z.y., Liu, X.y., Shi, X., Qiu, Z.z., Qin, H., Jia, P.y., Qin, Y. and Pan, W.g., 2019. “Removal of NO by using sodium persulfate/limestone slurry: Modeling by response surface methodology”. *Fuel*, Vol. 254, p. 115612.
- Lockwood, F., Salooja, A. and Syed, S., 1980. “A prediction method for coal-fired furnaces”. *Combustion and Flame*, Vol. 38, pp. 1–15.
- Lowe, A., Wall, T.F. and Stewart, I.M., 1975. “A zoned heat transfer model on a large tangentially fired pulverized coal boiler”. *Symposium (International) on Combustion*, Vol. 15, No. 1, pp. 1261–1270.
- McAdams, W.H. and Hottel, H.C., 1954. “Heat Transmission”. In *Chemical Engineering Series*, McGraw-Hill Inc., New York, NY, chapter 4 - Radian, p. 553. 3rd edition.
- Montgomery, D.C., 1997. *Design and Analysis of Experiments*. John Wiley & Sons, Inc., 5th edition. ISBN 0-471-31649-0.
- Nienaber, E.C. and Auret, L., 2019. “Experimental modelling and plant simulation of spiral concentrators: Comparing response surface methodology and extended Holland-Batt models”. *Minerals Engineering*, p. 105833.
- Ström, B., 1980. “A simple heat transfer model for furnaces based on the zoning method”. *Wärme- und Stoffübertragung*, Vol. 13, No. 1-2, pp. 47–52.
- The MathWorks, I., 2012. “MATLAB -”.
- Tucker, R., 1986. “Direct Exchange Areas for Calculating Radiation Transfer Transfer in Rectangular Furnaces”. *Journal of Heat Transfer*, Vol. 108, pp. 707–710.
- Zhao, H., Shen, J., Li, Y. and Bentsman, J., 2017. “Coal-fired utility boiler modelling for advanced economical low-NO<sub>x</sub> combustion controller design”. *Control Engineering Practice*, Vol. 58, No. x, pp. 127–141.