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EVALUATION OF UNBURNED FUEL IN THE MODELING OF THE COMBUSTION PROCESS IN A 360 MW COAL-FIRED BOILER

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Abstract. *This paper explores the practical results of an integral approach model of the coal combustion process and mainly the heat transfer mechanisms to be applied to the furnace of a* $360\,\mathrm{MW}$ *thermal power plant. The model is based on Hottel's zone method, and coal energy release is considered by taking into account its higher heating value. Aiming to bring higher detailing to this simplified model, the adoption of an unburned-fuel-fraction is also proposed. Four different unburned-fuel-fraction profiles were assessed. The model prediction for the gas temperature at the furnace exit plane deviates only* $8\,\%$ *to experimental data. Regarding the different unburned-fuel-fraction profile,* $-1.5\,\%$ *relative deviation was found when comparing the model with a fixed unburned-fuel-fraction, and the model that considered a linear-descendent profile. Nonetheless, the results of different unburned-fuel-fraction profiles suggest that the model could be fitted to represent more accurately the combustion process, by adopting different profile setups.*

Keywords: *Coal Combustion, Zonal Method, Unburned-fuel, Radiation.*

1. INTRODUCTION

Despite global efforts to boost the share of renewables in the energy mix, fossil fuels will remain on the basis of the world energy matrix in the near future. Forecast scenarios for developed countries as Germany, where clean energy is fostered, indicate that coal will occupy 25% of the country energy matrix in 2030 and will remain as a relevant option at least until 2050 (Hübel *et al.*, 2017). Coal-fired power plants will be kept operating for longer, reason why it is so important to improve efficiency and mitigate environmental impacts. Process computational modeling is an attractive approach to study ways to improve efficiency, control emissions, and ensure safe operation in power stations operating with coal.

Basically, furnace models can be divided into two groups: i) Complete mathematical models based on Computational Fluid Dynamics (CFD) and ii) Reactor Network Models (RNM) (Sankar *et al.*, 2019). Recently, statistical approaches based on large data amounts have been explored as well. Computational Fluid Dynamics is a detailed approach to model transport phenomena with high accuracy that has been widely used in recent years. The literature review indicates that accuracy improvement cames prior to response time (Mahmoodi *et al.*, 2017). CFD models usually demand high computational capacity, and even nowadays with powerful processing devices, the simulations of real scale boilers and furnaces easily take hours or days to converge (Constenla *et al.*, 2013; Crnomarković *et al.*, 2016; Sankar *et al.*, 2019). From a different point of view, statistical modeling and artificial intelligence (AI) algorithms use large amounts of data in order to estimate process behavior. Although fast and powerful, they depend on both reliable data and specialist knowledge. There are situations where this type of model cannot foresee unusual process conditions, moreover, data acquisition is a challenge once it depends on complex control systems, and the accuracy of measurement instruments (Wang *et al.*, 2018).

Reactors Network Models (RNM) are based on dividing the domain into a set of reactors, creating a solution mesh not as refined as CFD approaches. Concerning the combustion process, some strategies can be adopted in order to improve calculation routines, avoiding expensive solution times. The same precaution must be respected when solving radiative heat exchange balances, whose non-linearities can easily be time-consuming, even for simple geometries (Zhang *et al.*, 2014). In this context, the zonal method (Hottel and Cohen, 1958) is an effective alternative for modeling the thermal performance of enclosures with participating media like industrial furnaces (Ebrahimi *et al.*, 2013), combining accuracy to solution time.

The zonal method was explored by Johnson and Beer (1973) industrial furnaces applications, where an emissivity model for clouds of soot particles as a weighted sum of gray gases was proposed. Experimental data were gathered in the small scale furnace of the International Flame Research Foundation (IFRF) at IJmuiden, Netherlands. The authors reported small deviations for the model results of gas temperature and heat flux when compared to measured data. (Smith and Smoot, 1980) modeled the combustion and gasification process of pulverized coal, accounting for moisture evaporation, devolatilization, and char combustion. The research focused on the detailed phenomena description despite the limited processing capacity at the time the study was carried out. The zonal method is still suitable approaches for radiation in industrial furnaces nowadays, especially if current computational processing capacity is taken into consideration. Zhao *et al.* (2017), for instance, modeled a Low-NO_X utility boiler furnace by subdividing the furnace domain into slabs, where energy balances allow for the calculation of gas temperature and heat fluxes. The combined application of the RNM with a gray box model assessed by the authors suggests the suitability of ZM to control-oriented models.

The present paper explores simplified modeling of the heat transfer and coal combustion in an industrial furnace of a power plant boiler. To do so the model is based on Hottel's zonal method (ZM). The influence of unburned fuel is assessed for the case study of PECÉM power station. Different relations on unburned fuel fractions were compared.

2. MATHEMATIC MODELING

The adopted combustion model takes as inputs the coal composition and the coal to air rate. Higher heating value and lower heating value are informed in laboratory reports from PECÉM power station. The energy introduced in the system by the fuel Q_{comb} is then calculated by Eq. 1.

$$Q_{comb} \; = \; LHV_{coal} \, \dot{m}_{coal} \tag{1}$$

2.1 Zonal Method

Overall heat transfer phenomena occurring in the furnace domain are calculated by the zonal method (McAdams and Hottel, 1954), which consists of subdividing the non-isothermal and heterogeneous furnace domain into isotherm and homogeneous surface and gas-volume zones.

Radiation heat transfer is calculated by defining the Direct Exchange Area (DEA), which represent the fraction of radiant energy that leaves a given zone and directly reaches other given one, as a function of their geometry and the medium radiant characteristics. DEA can be determined by means of the following relations (Hottel and Sarofim, 1967):

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

$$\overline{g_i s_j} = \int_{V_i} \int_{A_j} \frac{\tau(r) K_i \cos\theta_j}{\pi r^2} dA_j dV_i, \tag{3}$$

$$\overline{g_i g_j} = \int_{V_i} \int_{V_j} \frac{\tau(r) \; K_i \; K_j}{\pi r^2} dV_j dV_i. \tag{4}$$

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[1]. Equation 2 indicates the DEA between two surface zones, Eq. 3 the exchange between a surface zone and a gas-volume zone and Eq. 4 the exchange between two gas-volume zones. In the present work, DEA was determined by the polynomial correlations proposed by Tucker (1986).

To account for multiple reflections inside the furnace the Total Exchange Area (TEA) was calculated. The TEA calculation procedure, presented by McAdams and Hottel (1954) and Hottel and Sarofim (1967), consists of setting to zero the emissive power of all zones but one, and accounting the multiple reflections for this condition. This operation is performed until all zones' contributions are computed, and an overall relation is found.

An energy equation must be stated for each zone, leading to a closed system of **N** equations and **N** unknowns. For a surface zone, considering the boundary condition of unknown temperature, the energy balance equation is

$$\sum_j \overrightarrow{S_j S_i} E_{s,j} + \sum_j \overrightarrow{G_j S_i} E_{g,j} - A_i \epsilon_i E_{s,i} + h_i A_i (T_{g,k} - T_{s,i}) = Q_{net,i}, \tag{5}$$

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 coming other surfaces and gas zones, respectively. The third term represents the emitted radiation. Convection is accounted for the relation $h_i A_i (T_{g,k} - T_{s,i})$, and the energy rate through the surface in [W] is represented by $Q_{net,i}$. The gas-volume energy equation can be written as

$$\sum_j \overrightarrow{G_j G_i} E_{g,j} \; + \; \sum_j \overrightarrow{S_j G_i} E_{s,j} \; - \; \sum_j 4 a_{g,n} \, K_n \, V_i \, E_{g,i} \; + \; Q_{e,i} \; = \; Q_{u,g_i} \; - \; Q_{H,_i} \; - \; Q_{c,i}. \tag{6}$$

[1] K stands for the gas absorption coefficient integrated over the entire spectrum.

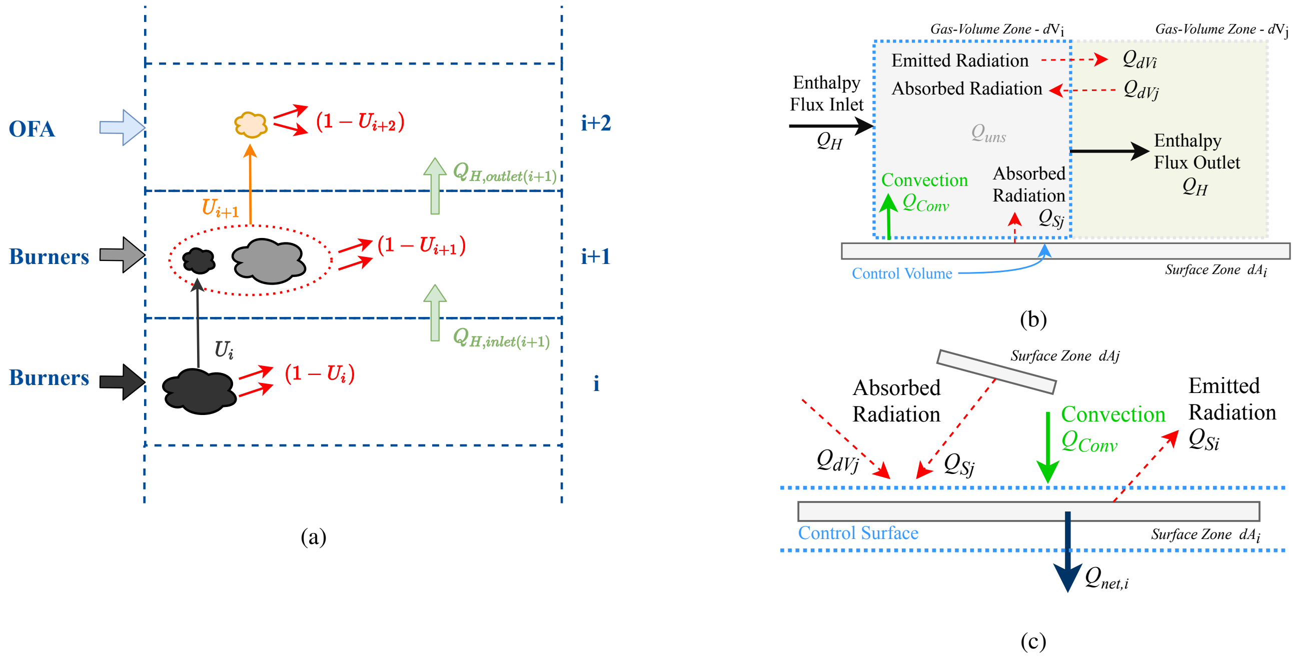


Figure 1: Model arrangements: (a) Energy released by coal burning and the fraction of uburned coal U_i, (b) Energy balance in gas volumes zones, (c) Energy balance in surface zones.

Equation 6 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 gas between the control volume inlet and outlet $Q_{H,_i}$, plus the convection from any surface adjacent to the gas-volume $Q_{e,i}$. Overall energy balance is presented in Fig. 1b for gas volume zones, while the balance for surface zones is presented in Fig. 1c. Only gas volumes facing surface zones experience convective heat transfer.

Coal energy release during combustion was modeled as depicted in Fig. 1a. In the gas volume, i pulverized coal enters, and only a fraction of it $(1-U_i)$ is considered to burn in the volume. The unburned coal fraction U_i is transferred to the next gas volume $(i+1)$. Equation 7 represents the amount of energy released in the combustion processes in gas volume $(i+1)$.

$$\dot{Q}_{c,(i+1)} = \left(\dot{Q}_{t,i} + HHV\dot{m}_{coal,(i+1)}\right)\left(1-U_{(i+1)}\right), \tag{7}$$

where $\dot{Q}_{t,i}$ is the fraction of the energy from coal introduced in gas volume i that will be released only in $(i+1)$,

$$\dot{Q}_{t,i} = HHV\dot{m}_{coal,i}U_i. \tag{8}$$

The term $HHV\dot{m}_{coal,(i+1)}$ is the energy introduced in the gas volume by the pulverized coal, Eq. 1, and the fraction of energy actually released in the gas volume is represented by $\left(1-U_{(i+1)}\right)$. Different unburned fraction relations throughout the furnace were assessed.

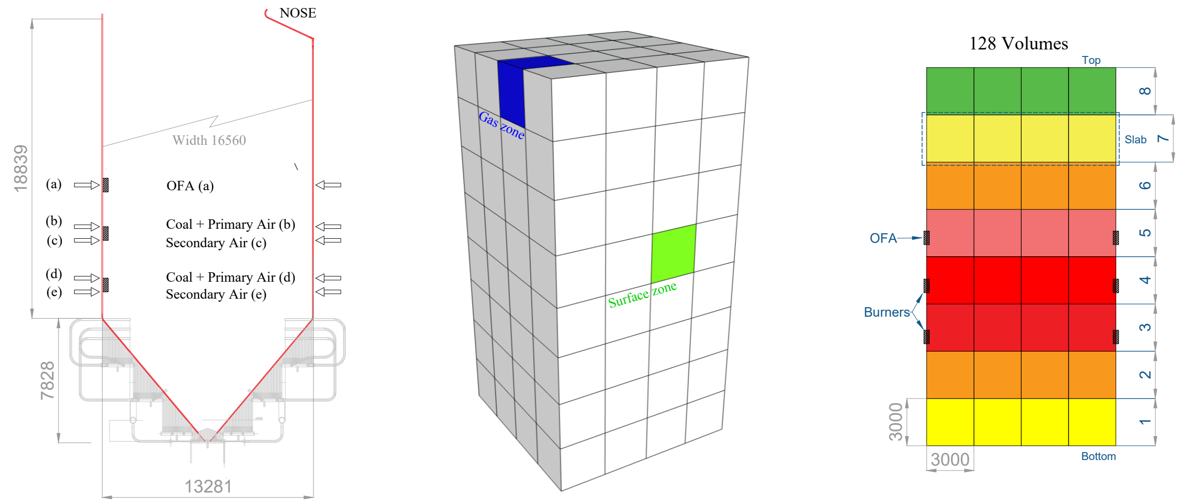
Water wall temperature was defined by estimating the steady-state, one-dimensional heat flux q_{wall}, represented by Eq. 9 (Arpaci, 1966) for constant thermal conductivity.

$$Q_{wall} = N_{tubes}\frac{2\pi\, L\, k_{cond}\, (T_{wall}\; - \; T_{water})}{2\ln\left(\frac{r_o}{r_i}\right)} \tag{9}$$

Considering L the furnace height, and N_{tubes} the total number of water-wall tubes Total transfeer area was calculated. Wall heat rate was estimated as $Q_{wall} = \dot{m}_{water}\,(h_{steam} - h_{liquid})$, and a value of 3.5×10^8 W was found. Therefore, the wall temperature T_{wall} was estimated as 686 K. The estimated wall temperature agrees in magnitude with the reported value of 600 K from (Vuthaluru and Vuthaluru, 2006) in a CFD modeling of a 500 MW wall-fired utility boiler. The calculated temperature is close to the expected water phase-change temperature inside the tubes, $T_{steam} = 633.8$ K, correspondent to the saturated steam temperature at the operating pressure of $P_{steam} = 188.1$ bar.

3. CASE STUDY

First, the modeling was previously validated by been compared to the results of an experimental setup, as presented in (Ermel, 2019). Then, a case study was carried out by applying the presented methodology in the coal-fired 360 MW electric generation boiler of EDP PECÉM power station. The power plant is located in São Gonçalo do Amarante in Ceará - Brazil. Figure 2a present the furnace dimensional scheme. There are two lines of burners in opposed walls totalizing 24 burners in a frontal burning arrangement. Over fire air is positioned above burners to complete the combustion process, ensuring excess air condition. The simulated mesh is composed of 128 gas volumes, 128 surface zones in the side-walls,



(a) (b) (c)

Figure 2: Furnace domain discretization composed of cubes with three-meter side. (a) Dimension of PECÉM's boiler furnace (b) Zoning scheme to fit furnace domain with 128 gas volumes (c) Gas-volumes at the same height are considered to be isothermal, and this unit is called Slab.

and 32 surface zones in the furnace bottom and top (Fig. 2b). Gas zones in the same height are considered to a Slab with homogeneous composition, and sharing equally the energy released in the combustion, as displayed in Fig. 2c. Although being homogeneous regarding the composition, gas zones pertaining to a given slab can present different temperatures, since they experience different heat exchange conditions (radiation, convection). For the selected mesh only cubes and squares with sides of $3\,\mathrm{m}$ were adopted to allows for the DEA correlations proposed by Tucker (1986). Table 1 displays the operational parameters used in the simulations. Reports of experimental measurements informed by the power plant

Table 1: Operational parameters from PECÉM's power plant boiler, used in all simulations.

Parameter	Value
Coal flowrate $[\frac{\mathrm{kg}}{\mathrm{s}}]$	1.56
Primary and Secondary air flowrate $[\frac{\mathrm{kg}}{\mathrm{s}}]$	12.02
OFA air flowrate $[\frac{\mathrm{kg}}{\mathrm{s}}]$	5.60
Inlet coal flowrate $[\frac{\mathrm{kg}}{\mathrm{s}}]$	1.56
Primary and Secondary temperature [K]	550.00
OFA air temperature [K]	450.00

indicate that the temperature at the furnace exit plane is approximate $1432\,\mathrm{K}$. This value is consistent with reports from several works in the literature, that explored modeling of similar power plant furnaces (Constenla *et al.*, 2013; Chen *et al.*, 2017; Madejski, 2018).

Four different relations for the unburned-fuel-fraction were evaluated aiming to determine the model behavior concerning this phenomenon, and if this model could deliver answers suitable to be used by the power station staff. Each configuration is described in the following topics.

3.1 Perfect Stirred Reactor

The first assumption regarding the fraction of unburned fuel was consisted of considering the slabs as perfect stirred reactors. Therefore, all the energy introduced by the fuel in the slab (i) is transferred to the product gas contained in it, as detailed in Eq. 6. In this approach the term U_{i+1} in Eq. 7 must be set to zero, for all gas volumes in the furnace domain. This means that all fuel entering the volume will burn in the same volume.

3.2 Constant - First approach

To describe the fraction of fuel that does not participate in the combustion process inside the gas volume (i), a constant fraction of unburned fuel was adopted as the second approach. In this configuration, only the slabs with burners were assigned an unburned fuel fraction of U_i= 0.2. All the other volumes were considered as PSR (U_i= 0.0). Hence, energy release due to the combustion process only takes place in the slabs with burners i, and $(i + 1)$.

3.3 Constant - Second approach

The second approach considered that to all the gas volumes a value of U_i= 0.2 is assigned. This way the chemical energy present in the pulverized coal is never fully released since only the fraction $(1 - U_i)$ is released in each slab.

3.4 Linear

The fourth evaluated model uses an inverse linear relation to estimating the fraction of unburned fuel in each slab. It was considered that the highest fraction occurs in the first line of burners, slab i. The fractions decrease linearly up to zero in the last slab. Table 2 resumes the simulated unburned fuel relation for each one of the assessed approaches.

Table 2: Resume of the unburned fuel fractions U adopted for each simulation.

Gas volume (Slab)	Case 1 (PSR)	Case 2 (Cte)	Case 3 (Cte)	Case 4 (Linear)
8	0.0	0.0	0.2	0.00
7	0.0	0.0	0.2	0.04
6	0.0	0.0	0.2	0.08
5	0.0	0.0	0.2	0.12
4	0.0	0.2	0.2	0.16
3	0.0	0.2	0.2	0.20
2	0.0	0.0	0.0	0.00
1	0.0	0.0	0.0	0.00

4. RESULTS

The first model proposes that every slab, and moreover, each gas zone is a perfect stirred reactor. Therefore, All coal entering that zone will immediately react, and its energy is transferred to the combustion gas. Although not been a realistic assumption, this model predicts an average gas temperature of $1453.5\,\mathrm{K}$ in the furnace outlet plane. This result differs only $1.5\,\%$ from the experimental measured reported by the power station technical staff, reason why it was chosen as the standard simulation to be compared with.

Results of models prediction on each slab temperature along the furnace height field are presented in Fig. 3. The temperature fields clearly display that all models behave similarly. The most significant difference arises when comparing the results of case 1 with the other cases. The same temperature is predicted for slabs three and four, while in the other cases the highest temperature is registered only in slab four. This result is expected as long as in case 1 the same amount of coal is admitted in both slabs. The temperature prediction of case 2, case 3 and 4 are very similar as presented in Fig. 3. The differences among the temperature results predicted by each model are better highlighted in Fig. 4. A similar trend is observed for all the simulated cases, however, a higher deviation occurs when case 1 is compared to the other cases. The relative deviation between the simulated cases and the reference model (case 1) is presented in Fig. 5a, where an interesting behavior can be observed. Considering case 1 as the standard to be compared with, the relative deviation of the other cases is approximately $7\,\%$ positive for slab one, two, and three. The deviation decreases near to $1\,\%$ in slab four (which the highest temperature is predicted). From slab five on, the relative deviation trend changes to approximately $5\,\%$ negative.

Other interesting behavior is the relative deviation between the temperature results of case 3 and case 4, presented in Fig. 5b. In this comparison, a maximum relative deviation of $-1.6\,\%$ is observed. In other words, despite the big difference between the results of case 1 and all other cases, it seems that only the consideration of an unburned fuel fraction in slabs 3 and 4, generates this difference. Further detailing in this parameter, such as the configuration set in cases 3 and 4 does not result in significant deviations in model comparison.

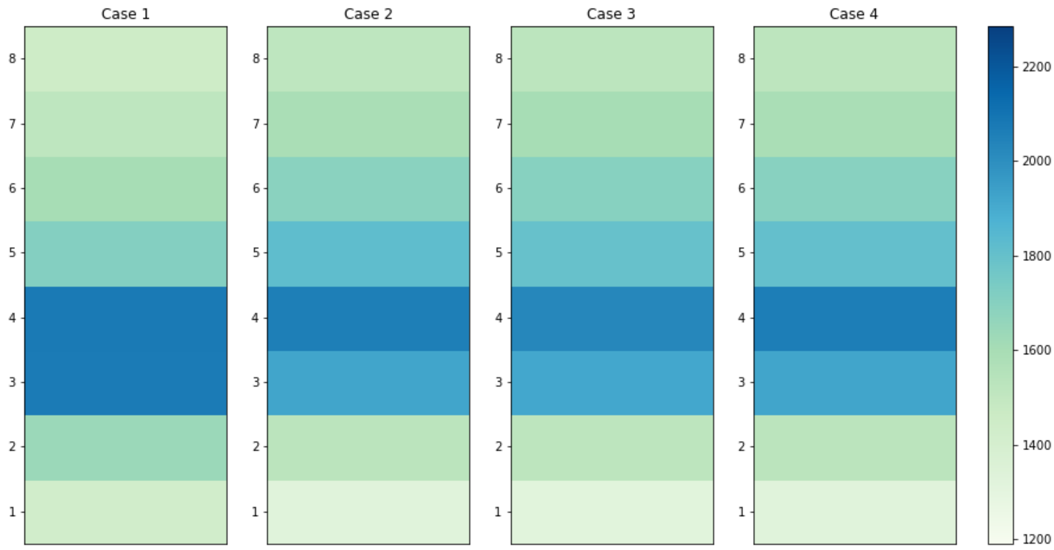


Figure 3: Temperature field predicted by each simulated model.

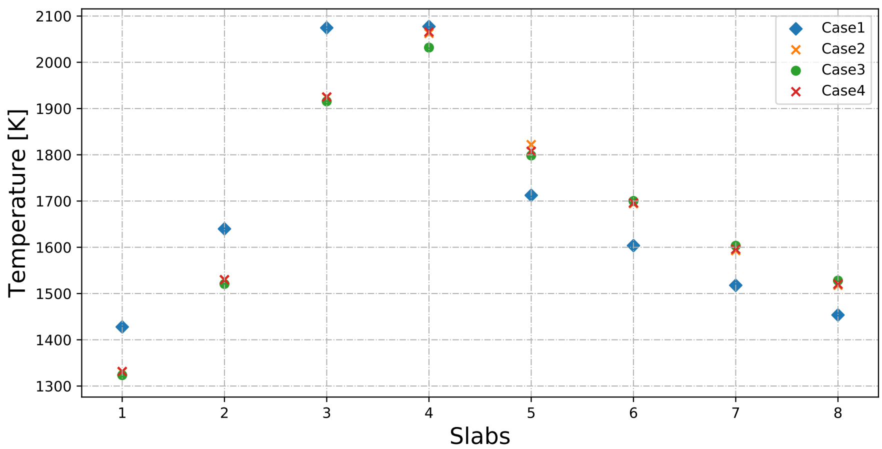


Figure 4: Average temperature results for each slab along furnace height.

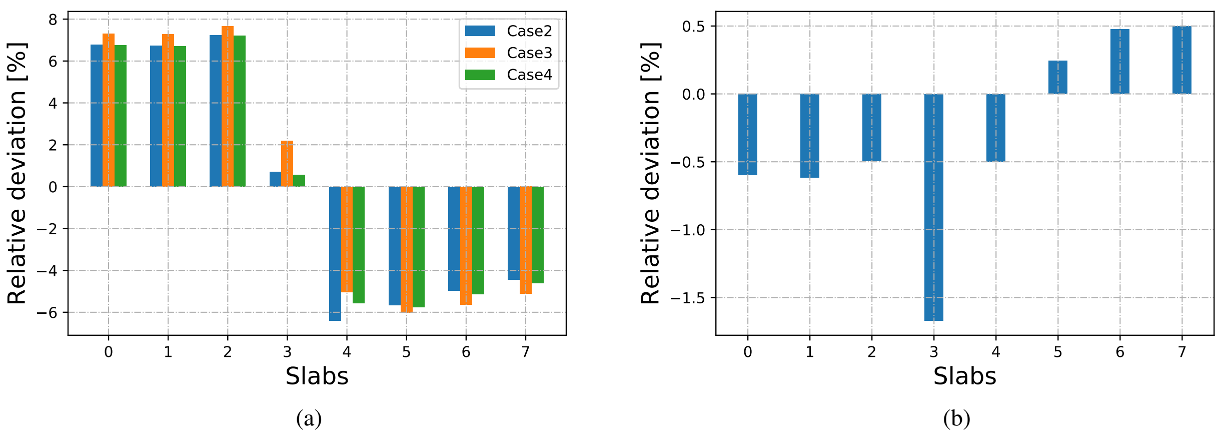


Figure 5: Relative deviation of temperature predictions for each slab along the furnace height: (a) Case 2, 3 and 4 compared to case 1 (b) Comparison between case 3 and 4.

5. CONCLUSION

A fast response model of the coal combustion process and heat transfer inside the furnace of a power plant steam generator is presented. The proposed integral model, based on Hottel's zonal method, is composed of 128 gas zones plus 160 surface zones. The modeling was capable of predicting the furnace outlet gas temperature with a maximum relative deviation of $8\,\%$. Regarding the models considering different unburned fuel fractions, the most significant deviation was observed when the unburned fraction is not considered at all, which is named case 1, and considered all slabs as PSRs', and the total amount of coal entering a slab is considered to be immediately burned, with the energy transferred to the combustion gas. All models presented a similar trend, which is also compatible with a real furnace temperature profile found in the literature. It is interesting that among the cases that considered different fractions of unburned coal along with the furnace slabs (cases 2, 3, and 4), no significant difference was found for temperature prediction. Comparing cases 3 and 4 a maximum relative deviation of $-1.5\,\%$ was observed, while the average deviation remained $-0.3\,\%$. Nonetheless, it is necessary to review more carefully the proposed unburned fuel fraction profiles, as all results predicted very high temperatures in the burning region. Only constant fractions were adopted, and in case 4, a linear decrease was studied. It is possible that other profiles, such as sinusoidal or logarithmic curves could better represent the gas temperature along with the furnace height. Furthermore, a comprehensive CFD model of the furnace has been developed. Data from this CFD model will allow for the model calibration. This way the presented model will serve as a support tool to the power plant operation staff, by quickly predicting the temperature field along with pollutant emission.

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