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A zero-dimensional model used as a basis for numerical modelling of OP-650 boiler

The numerical modelling of power boiler furnaces is often performed in the engineering practice. Quite often, however, the balance calculations of the entire boiler are not carried out. In this case, the flue gas temperature at the furnace outlet results from the numerical model and depends on the adopted assumptions (e.g. wall fouling or emissivity). However, the value determined in this way may be wrong, and the presented calculation method makes it impossible to verify it. One of the ways to improve the numerical model accuracy is the verification of the flue gas temperature at the furnace outlet value by calculations fully balanced by a zero-dimensional (0D) model based on measuring data. The numerical calculations should be carried in such a way that the average temperature at the furnace outlet in the computational fluid dynamical (CFD) model equals the temperature obtained from the 0D model. At the same time, the matching of this temperature should result from carefully selected assumptions of the numerical model, which have to correspond to the actual phenomena occurring in the furnace. This model presents the verification of the CFD model for the OP-650 boiler of a 225 MWel power unit. The results of numerical modelling of boiler according to non-premixed combustion model with mixture fraction/PDF (probability density function) approach was presented. Also numerical modelling of boiler with species transport model with volumetric reactions and finite rate chemistry was done.

1 Introduction

The numerical modelling of power boiler furnaces is often performed in the engineering practice. Quite often, however, the balance calculations of the entire boiler are not carried out. In this case, the flue gas temperature at the furnace outlet, t''_k, results from the numerical model and depends on the adopted assumptions (e.g. wall fouling or emissivity). However, the value determined in this way may be wrong, and the presented calculation method makes it impossible to verify it. One of the ways to improve the numerical model accuracy is the verification

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of the t_k'' value by calculations fully balanced by a zero-dimensional (0D) model based on measuring data. The numerical calculations should be carried in such a way that the average temperature at the furnace outlet in the computational fluid dynamics (CFD) model equals the temperature obtained from the 0D model. At the same time, the matching of this temperature should result from carefully selected assumptions of the numerical model, which have to correspond to the actual phenomena occurring in the furnace.

Adopted model presents the verification of the CFD model for the OP-650 boiler of a 225 MW_{el} power unit. The OP-650 boiler is a two-pass radiant boiler, fired with pulverised hard coal, with a natural water circulation with steam reheat. The furnace has the shape of a rectangular prism with lateral dimensions of 19.2×9 m. The boiler proper tube material is K-18. The walls of the boiler proper are not tight; tubes with a diameter of ∅57×6.3 are arranged with a 60 mm pitch. The boiler is fired by swirl burners installed on the front wall. The boiler is fed by 4 MKM-33 ball-ring mills with a maximum capacity of 33 t/h. Each mill feeds 4 swirl-type pulverised fuel burners, located on the front wall of the boiler proper. The burners are enclosed in a common secondary air-box.

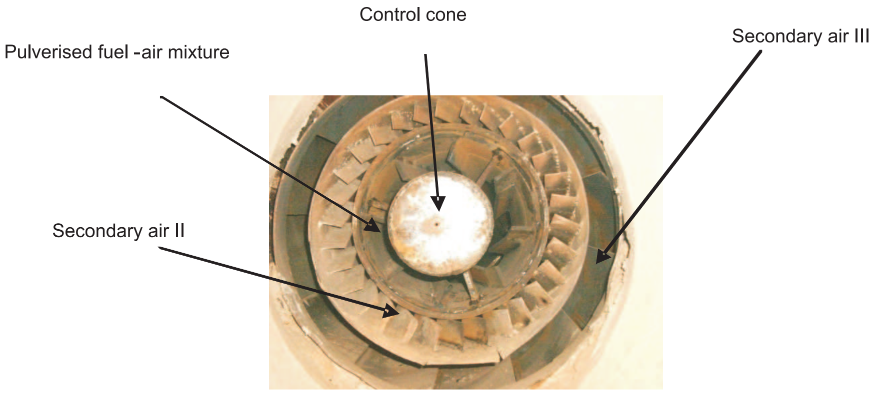

Figure 1. Pulverised fuel burner D1 together with the description of individual outflow zones; swirl vanes visible.

Through the burners 'secondary air' is fed in the form of a covering composed of the pulverised fuel-air mixture supplied by the mills. Secondary air dampers control the outflow of 'tertiary air'. Figure 1 presents a pulverised fuel burner together with the description of individual outflow zones. The marking, e.g. A1 to A4, means that the burners are fed from a single mill marked as A (Fig. 2).

The burners marked as R1–R6 (Fig. 2) are used only to feed overfire air (OFA) to the furnace. The amount of the overfire air is adjusted by the appropriate opening of the secondary air dampers. Figure 2 presents the distribution of pulverised fuel burners and the OFA nozzles.

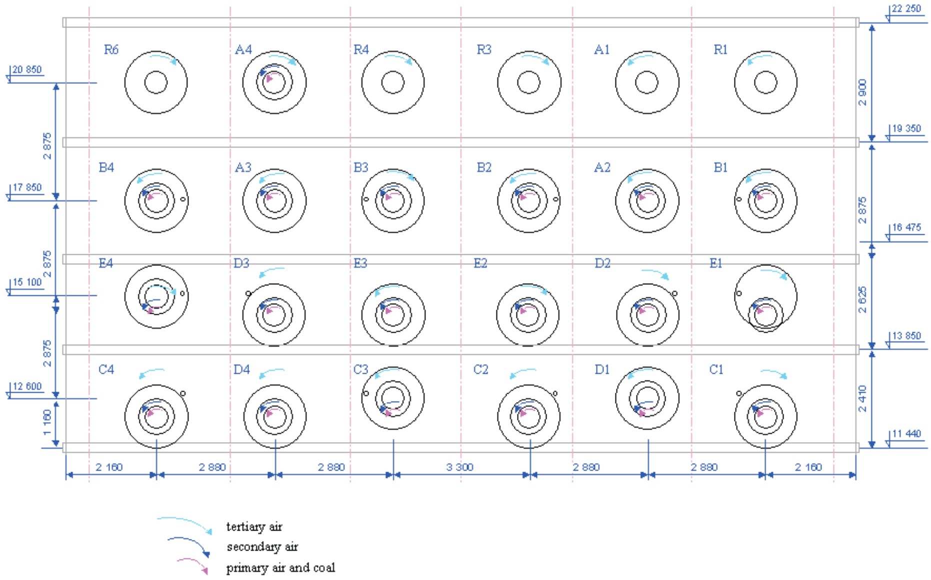

Figure 2. The distribution of pulverised fuel burners and the OFA nozzles on the front wall of the boiler (view from the boiler inside).

2 Boiler calculations using the 0-dimensional model

The actual distribution of temperatures and mass flows in the OP-650 boiler is found by measurements. The first stage of the calculations is to create a 0D model of the OP 650 boiler for the measuring conditions. In contrast to measurements which are always burdened with unavoidable errors, the model is fully balanced and the average temperature of the flue gases at the furnace outlet obtained using it may be considered as highly reliable. The 0D model employs the methodology presented in [1–3]. To perform the furnace calculations, the CKTI method [1,2] is used. This method based on Russian studies was developed and is commonly used in Poland. A technique based on studies conducted at the Silesian University of Technology [3] is used to perform the calculations of the convection part of the boiler. Compared to the method [1,2] it gives a much better accuracy because it is based on testing carried out in domestic pulverised fuel boilers.

The following values (considered as correct) obtained from measurements are assumed for the calculations:

- the mass flows of water, steam and injection;
- the pressure of agents;
- the temperature of agents at the boiler inlet.

The calculations are conducted for the data determined by measurements at the facility which are listed in Tabs. 1, 2 and 3. Table 2 shows the hard coal parameters (grain size in terms of the content of grains larger than x). As a result of the calculations performed using the presented model, the flue gas temperature at the furnace outlet with the value of $t_k'' = 1136$ °C is obtained.

Table 1. Comparison of the boiler operating parameters (obtained from measurements)

Data	Unit	**C**
Air mass flow I – burners A	kg/s	15.65
Air mass flow I – burners B	kg/s	17.24
Air mass flow I – burners D	kg/s	17.75
Air mass flow I – burners E	kg/s	18.82
Coal mass flow – burners A	kg/s	4.69
Coal mass flow – burners B	kg/s	6.03
Coal mass flow – burners D	kg/s	5.88
Coal mass flow – burners E	kg/s	5.96
Mixture temperature	°C	109
Air temperature II	°C	269
Air mass flow – OFA R1	kg/s	9.52
Air mass flow – OFA R2	kg/s	6.54
Air mass flow – OFA R3	kg/s	9.52
Air mass flow – OFA R4	kg/s	9.52
Air mass flow – OFA R5	kg/s	6.61
Air mass flow – OFA R6	kg/s	9.61
Air mass flow III – burners A	kg/s	20.21
Air mass flow III – burners B	kg/s	16.62
Air mass flow III – burners D	kg/s	10.84
Air mass flow III – burners E	kg/s	15.19
Air mass flow II	kg/s	25.86

Table 2. Coal grain size.

x	R_x
μm	%
88	33.97
102	27.55
120	20.89
150	12.92
200	5.56

Table 3. Coal analysis (as-received state).

Q_i^r	kJ/kg	21224
A^r	%	21.2
W_t^r	%	12.55
C^r	%	56.6
H^r	%	3.2
S^r	%	0.2
O^r	%	5.8
N^r	%	0.45

3 Numerical modelling of the OP-650 boiler

3.1 Modelling description and boundary conditions

The OP-650 boiler for a 215 MW power unit was modelled according to non-premixed combustion model with mixture fraction/PDF (probability density function) approach and also with species transport model with volumetric reactions and finite-rate chemistry. In Tab. 4 models used in calculation was presented. Reactions and parameters for combustion of volatile matter used in volumetric reactions in finite-rate chemistry was presented below (the group of coefficient: m, n, l, k was obtained based at coal compositions). For coal particle parameters for devolatilization and combustion models was selected on the basis of FLUENT program help.

$$C_m H_n O_l N_k + \left(\frac{m-l}{2} + \frac{n}{4}\right) O_2 \xrightarrow{k1} mCO + \frac{n}{2} H_2 O + \frac{k}{2} N_2$$

$$CO + 0.5_{O2} \xrightarrow{k2} CO_2$$

The modelling input data implemented into the FLUENT Inc. code [2] are presented above in Tabs. 1, 2 and 3. The contour of the furnace of the numerical model of the OP-650 boiler is shown in Fig. 3. The geometrical model and the numerical mesh (Fig. 4) composed of 1380996 numerical cells are made using the Gambit software – official preprocessor of Fluent code [6]. The modelled boiler includes geometrical components which significantly differ in the length scale. Therefore, the employed numerical mesh is made using the 'non-conformal' technique. In the entire area of the boiler and burners, a structural mesh is used whose individual numerical cells have the shape of cuboid solids.

Table 4. Sum models used in simulations [4].

Model	Nonnremixed combustion	Species transport model	
Two-phase model	Euler-Lagrange		
Turbulence model	k-ε		
Combustion model	Mixture fraction/PDF in chemical equilibrium with non adiabatic conditions	Volumetric reactions finite-rate chemistry	
		k1 reactions	k2 reactions
		A=5.012e+11 E=2e+8 J/kmol	A=2.239e+12 E=1.7e+8 J/kmol
	Gas absorption: wsggm-cell-based model, calculated upon CO2 and H2O concentration		
For coal particle			
Devolatilization	Single – rate model A1 = 312 000 E1 = 7.4e+7 J/kmol		
Combustion	Diffusion-kinetics model C1 = 5e+12 A = 6.7 EA = 1.32e+8 J/kmol		
Radiation model	P1	DO	
NO_x model			
Formation	Thermal and fuel pathways		
Concentration of OH and O	Partial equilibrium		
PDF turbulence interaction	Mixture mode	Temperature mode	
N intermediate	HCN/NH3/NO		
Char N conversion	NO		
Spherical shape of coal particle and Rosin-Rammler-Sperling distribution was used			

3.2 Modelling results

Figure 5 presents the thermal field in the plane of the furnace outlet window. Left side represents results of numerical modelling according to non-premixed combustion model while right side of figure showed results for species transport model. Figure 6 presents the content of NO in the plane of the furnace outlet window. Left side represents results of numerical modelling according to non-premixed combustion model and right side of figure showed results for species transport model.

4 Comparison of computational fluid dynamics modelling with zero-dimensional code

In order to obtain the flue gas temperature at the furnace outlet as the outlet window surface area average temperature of 1136 °C, the same values obtained

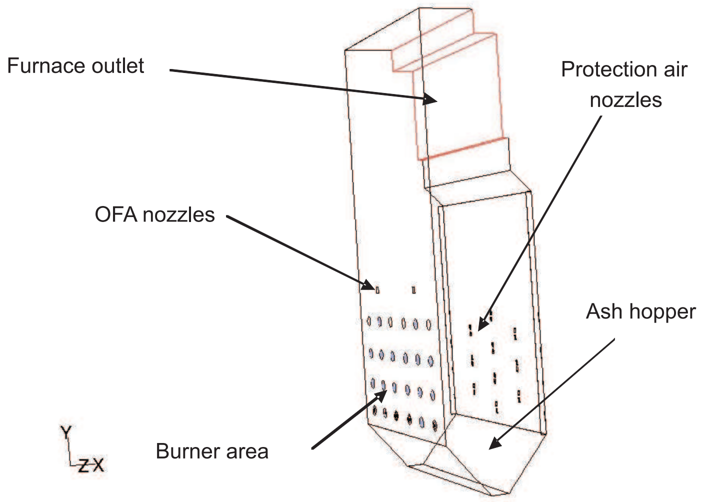

Figure 3. The contour of the OP-650 boiler furnace.

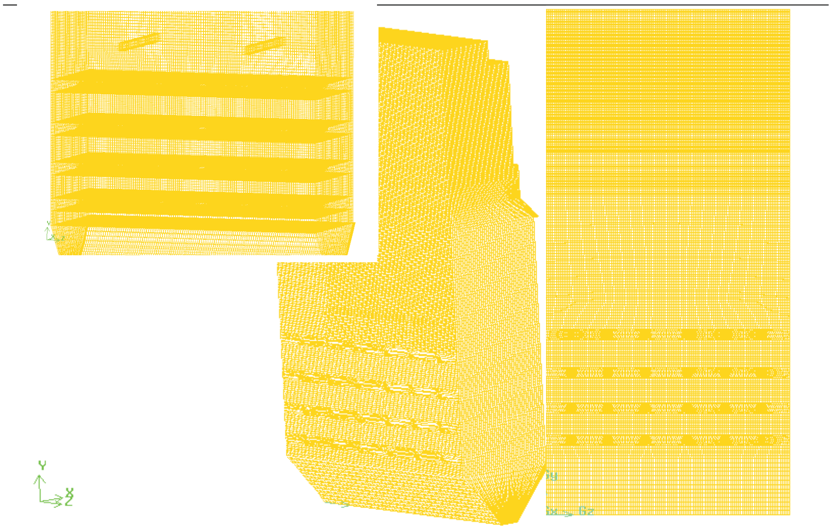

Figure 4. Gambit software numerical mesh of the OP-650 boiler furnace.

from the boiler measurements are entered as input data both into the numerical model and into the 0D model. Variant numerical calculations show that the match of the t_k'' value for all models is achieved if the furnace walls emissivity is assumed

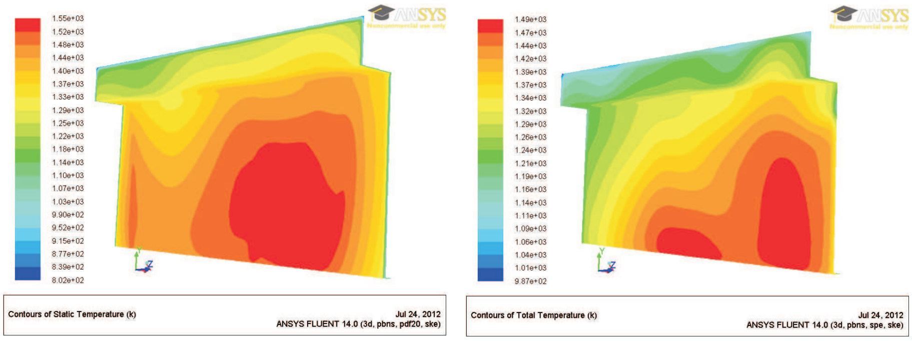

Figure 5. The thermal field in the plane of the furnace outlet window.

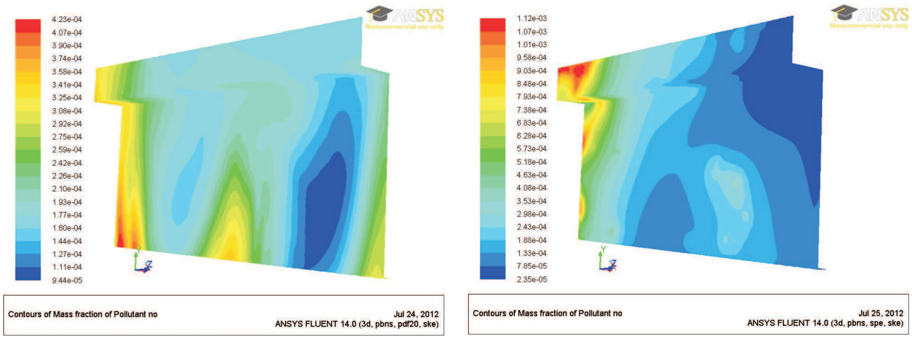

Figure 6. Content of NOx in the plane of the furnace outlet window.

at $\varepsilon_{sc} = 0.56$ for non-premixed combustion and 0.6 for species transport model. Because in practice it is impossible to measure the emissivity of the furnace walls, the verification presented in this paper is a good method of obtaining a numerical model which reflects the furnace operating conditions in a reliable way. The emissivity of ε_{sc} =0.56–0.6 is feasible for Polish pulverised fuel boilers fed with domestic hard coal. The furnace walls are in this case covered with a layer of loose ash deposit and no slagging is observed. Table 5 presents the composition of the fly ash typical of Polish boilers which forms deposits on the furnace waterwalls. Table 6 compares the temperature and the concentration of nitrogen oxides as NO_2 6% O_2 at the furnace outlet as the results obtained from CFD modelling, calculated using a zero-dimensional code and obtained from measurements after the boiler.

Table 5. Typical composition of the fly ash which forms deposits on the furnace waterwalls.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2
Unit of measure	%	%	%	%	%	%	%	%	%
Content	54.24	32.18	4.87	2.60	1.05	0.47	2.59	0.65	1.37

Table 6. Temperature and calculated and measured NO_2 concentration.

Data/Method	Nonpremixed Combustion	Species Transport Model	zero-dimensional model	Measurement
t [°C]	1136	1136	1136	–
NO_2 [mg/m_n^3]	423.1	443.5	–	435.8

5 Conclusions

1. It is shown that the obtaining of a reliable temperature at the furnace outlet by means of numerical modelling is possible using a zero -dimensional boiler model based on the data obtained from the boiler measurement.
2. The information concerning the emissivity of the boiler waterwalls found in this way may be useful in CFD modelling in the most common situation when the flue gas temperature at the furnace outlet is unknown.

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References

[1] Orłowski P., Dobrzański W., Szwarc E.: *Steam Boilers.* WNT Warsaw 1979 (in Polish).

[2] Kuznetsov N.W, Mitor W.W, Dubovski I.E, Karasina E.S:. *Standards for Thermal Calculations of Power Boilers.* Energia. Moskva 1973 (in Russian).

[3] Pronobis M.: *Heat Transfer in Boiler Convection Surfaces with Fouling.* Zeszyty Naukowe Politechniki Śląskiej, ser. Energetyka 115, Gliwice 1992 (in Polish).

[4] Hernik B.: *Investigations for Decreasing of Risk of Corrosion-Erosion in Boilers.* PhD thesis, Silesian University of Technology, Gliwice 2009 (in Polish).

[5] Ansys Fluent. Computational Fluid Dynamics, Ansys Inc., England, www.ansys.com

[6] Fluent. Computational Fluid Dynamics, FLUENT Inc., England

Zerowymiarowy model kotła jako podstawa do obliczeń numerycznych kotła OP 650

Streszczenie

W praktyce inżynierskiej często wykonywane jest numeryczne modelowanie palenisk kotłów energetycznych, przy czym często nie prowadzi się obliczeń bilansowych całego kotła. Temperatura spalin na wylocie z paleniska wynika wówczas z modelu numerycznego i zależy od przyjętych założeń (np. zanieczyszczenie ścian lub ich emisyjność). Tak wyznaczona wartość temperatury może jednak być błędna, a opisany sposób liczenia uniemożliwia jej weryfikację. Sposobem na poprawę dokładności modelu numerycznego jest weryfikacja temperatury spalin na wylocie z paleniska za pomocą w pełni zbilansowanych obliczeń modelem 0-wymiarowym opartym na danych pomiarowych. Obliczenia numeryczne powinny być tak prowadzone, aby średnia temperatura na wylocie z komory paleniskowej kotła w modelu CFD była równa temperaturze uzyskanej z modelu zerowymiarowego. Jednocześnie dopasowanie tej temperatury powinno wynikać z odpowiednio dobranych założeń modelu numerycznego, które muszą odpowiadać realnemu przebiegowi zjawisk zachodzących w palenisku. W niniejszej pracy dokonano opisanej weryfikacji modelu CFD dla kotła OP 650 do bloku 225 MW$_{el}$. Przedstawiono wyniki modelowania numerycznego kotła wg algorytmu *mixture fraction/PDF* – z wykorzystaniem modelu spalania *non-premixed* oraz wyniki dla modelu opartego na reakcjach objętościowych z wykorzystaniem modelu *finite-rate/eddy-dissipatio*n.