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Power and ecological characteristics of a buffer boiler supplied with coal and after-processing gases

The method for determination of power and ecological characteristics of a steam boiler, adapted for buffer burning of coal dust and waste gas fuels such as blast-furnace gas, converter gas and coke gas, is the work objective. By the characteristics we mean a relationship between the analyzed power parameter (e.g. efficiency or stream of chemical energy of hard coal) or ecological parameter (emission of harmful substances) and the chemical energy stream of each waste gas and boiler output. Power characteristics can be used to determine the effects of boiler work in changeable operational conditions.

1 Description of testing object

1.1 Description of boiler

OPG-230 steam boiler of natural medium circulation fired with hard coal as well as with blast-furnace, converter and coke gases that produces steam of pressure 9 MPa, was the testing object. The boiler is equipped with nine dust burners located at the front wall of heart chamber. On the side walls of heart chamber there are four gas burners where blast-furnace gas is burnt or gas mixture is burnt (with admixture of converter gas or coke gases).

1.2 Fuels used in the boiler

Coal used by the heat and power plant is of high calorific value in the range from 27000–29000 kJ/kg and has low sulfur content (in the range from 0.52 to 0.64%). Coal mean calorific value is 27700 kJ/kg.

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Gases burnt in the heat and power plant are byproducts in the production of pig iron (blast-furnace gas) and production of steel (converter gas) as well as generated during coke production (coke gas) in the coking plant. Collection of waste fuel gases, especially blast furnace gas by heat and power plant situated near the steelworks is economically justified [16]. Mean calorific value of blast-furnace gas is 3600 kJ/m_n^3 and changes in the range from 3200 to 4000 kJ/m_n^3. Converter gas is fed in as a mixture with blast-furnace and it has to enrich the mixture due its higher calorific value, which varies from 6800 kJ/m_n^3 do 9000 kJ/m_n^3. Mean calorific value of converter gas is 7 900 kJ/m_n^3. Calorific value of the mixture is in the range 3400–4400 kJ/m_n^3. Coke gas is used to light the boilers. It is a high caloric gas and its caloric value is about 17500 kJ/m_n^3. Its calorific value varies within the range between 16800 to 18300 kJ/m_n^3.

Co-incineration of steelworks waste gases with coal by the heat and power plant as well as changeability of content of gas mixture supplying the boiler causes unstable heat transfer conditions what has s significant impact on operational effects of the boiler. Thus it is reasonable to determine power and ecological characteristics of boiler in the heat and power plant that should include variable supply of fuel gases.

2 Boiler characteristics

Input-output model that is described by the below modeling quantities, is the base of the characteristics:

- independent input quantities: $\{x_k\}$, $k = 1, 2, 3, 4$, where:

  x_1 – boiler output, t/h,
  x_2 – chemical energy stream of burning blast-furnace gas, MW,
  x_3 – chemical energy stream of burning converter gas, MW,
  x_4 – chemical energy stream of burning coke gas, MW,

- dependent input quantities: $\{y_p\}$, $p = 1, 2, \ldots, 7$, where:

  y_1 – boiler power efficiency,
  y_2 – emission CO, kg/h,
  y_3 – emission CO_2, t/h,
  y_4 – emission NO_x, kg/h,
  y_5 – emission SO_2, kg/h,
  y_6 – dust emission, kg/h,

y_7 – chemical energy stream of burning coal, MW.

Characteristics of testing object are explained by the following relationship:

$$\mathbf{Y} = f(\mathbf{X}) \,, \tag{1}$$

where **Y**, and **X** are vectors of dependent and independent quantities, respectively. Figure 1 explains relationship (1).

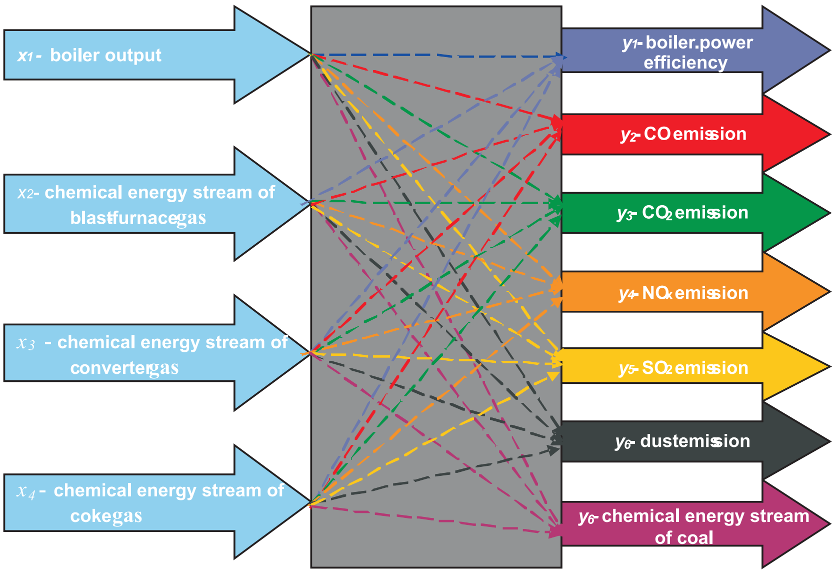

Figure 1. Characteristics of the testing object.

When selecting a design of experiments the function determining a given characteristics is very important. Function in a form of quadratic polynomial with first order correlations [7,14]:

$$y_p = b_0 + \sum_{k=1}^{k=3} b_k x_k + \sum_{k=1}^{k=3} b_{kk} x_k^2 + \sum_{k=1}^{k=3} \sum_{g=k+1}^{g=3} b_{kg} x_k x_g \,, \tag{2}$$

where b_0, b_k, b_{kk}, b_{kg} are polynomial coefficients (structural parameters), determined by statistics methods basing on the specially taken measurements of the boiler. Scientific methods for experiments designing were used to determine the design of experiments.

3 Methods for determination of characteristics

3.1 Use of design of experiment method

Design of experiment is a list of selected independent input quantities accepted in each measurement. In the tests it was assumed that the number of values of each independent quantity will be the same. From the theory of experimental design it results [14] that it is enough to take measurements for two values of each independent quantity to determine linear characteristics of an object. However, in the case of characteristics described by non-linear functions it is necessary to include at least three values of each independent quantity. Non-linear characteristics of an object were assumed "a priori" in the presented paper. That is why three values of each independent input quantity were included in the carried out experiments. A procedure of coding (standardization) of values of experimental design levels was used to simplify and standardize the design of experiments. Each considered k-th independent input quantity takes values from the lowest value $x_{(min)k}$ to the highest value $x_{(max)k}$. These values can be normalized to the levels –1; 0 and +1 with the use of the following coding relationship [6]:

$$\tilde{x}_k = \frac{2x_k - x_{(\min)k} - x_{(\max)k}}{x_{(\max)k} - x_{(\min)k}} \,. \tag{3}$$

From relationship described by Eq. (3) it results that if x_k reaches the value of $x_{(min)k}$ then $\tilde{x}_k$ standardized variable reaches –1. When x_k reaches the mean value (which is arithmetic mean of $x_{(max)k}$ and $x_{(min)k}$), the$\tilde{x}_k$ standardized variable reaches 0, while in the case when x_k reaches the value of $x_{(max)k}$, the $\tilde{x}_k$ standardized variable reaches +1. Described procedure of coding the variables enables a uniform recording in a design, regardless of the character and values of independent input quantities.

Taking measurements according to the complete design of experiments would be difficult to carry out in the case when 4 independent quantities would be taken into account, including 3 values of each of them, because it would require 81 series of measurements [14]. Due to economic limitations (relatively high cost of a measurement) there was a need to use a design, in which the number of necessary measurements would be smaller, what would first of all reduce the cost and time of testing [6].

Determination of object characteristic lies in a determination of polynomial (2) coefficients. Total number of coefficients of quadratic polynomial with correlations of the first degree order for 4 factors is [14]:

$$n_b = \binom{i+2}{2} = \frac{(i+1)\,(i+2)}{2} \;, \tag{4}$$

where i is the number of independent input quantities. For $i = 4$ it is obtained $n_b = 15$. Thus, it is justified to reduce a number of equations in a complete design of experiments, but maximally to the number of unknown coefficients. In a polynomial for four factors there are 15 approximation coefficients.

The approximation coefficients will be determined by a diagonal form information matrix $\mathbf{x}^T\mathbf{x}$ [1,12,18]:

$$\mathbf{b} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} \;. \tag{5}$$

In the case of using the fraction design a number of indispensable measurements is limited to $3^{4-1} = 27$ measuring series [6].

When using the fraction design a number of obtained equations is also significantly higher that number of parameters of identified model. In such case we have unsaturated design of experiments, for which the following relationship takes place:

$$n > n_b \;, \tag{6}$$

where n, n_b denote the numbers of measuring points, and parameters of identified model, respectively.

The fraction design is obtained on the basis of complete design of experiments through resignation of some measuring systems [6,14]. To determine which equations of a complete design can be omitted a generating function of design [14], in which it was assumed that one of standardized input variable, e.g. $\tilde{x}_4$, is equal to a correlation of the first order of the rest standardized variables, was accepted:

$$\tilde{x}_4 = \tilde{x}_1\tilde{x}_2\tilde{x}_3 \;. \tag{7}$$

After analyzing the fraction design it was deiced to limit a number of measuring points in experimental design by excluding measuring systems, which are not in accordance with the operational reasons. If blast-furnace gas is not used also converter gas is not fed, i.e.:

$$\text{if} \quad \tilde{x}_2 = -1 \;, \quad \text{then} \quad \tilde{x}_3 = -1 \;. \tag{8}$$

Due to that the design including 19 measuring systems was obtained (Tab. 1) The reduced design of experiments was realized.

Table 1. Determined values of measuring points.

No.	Fraction design $n = 3^{4-1}$ if $\tilde{x}_2$ = -1, then $\tilde{x}_3$=-1			
	$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$	$\tilde{x}_4$
1	-1	-1	-1	-1
2	-1	0	-1	0
3	-1	0	0	0
4	-1	0	1	0
5	-1	1	-1	1
6	-1	1	0	0
7	-1	1	1	-1
8	0	-1	-1	0
9	0	0	-1	0
10	0	0	0	0
11	0	0	1	0
12	0	1	-1	0
13	0	1	0	0
14	1	-1	-1	1
15	1	0	-1	0
16	1	0	0	0
17	1	0	1	0
18	1	1	-1	-1
19	1	1	0	0

3.2 Description of measuring method

The measurements were taken during boiler operation at its three capacities (150, 180 and 210 t/h). During measurements the scheduled design was realized, i.e. measurements were taken for three chemical energy streams of blast-furnace gas (0, 62.5 and 125 MW), three ranges of chemical energy streams of converter gas (0, 14 and 28 MW) and three ranges of chemical energy streams of coke gas (0, 62.5 and 125 MW). During measurements the systems for automatic control of water level in the boiler drum, of steam temperature and of underpressure in the hearth chamber, were in operation. During measurements the indications of control devices, installed by a measuring company, as well as indication of operational gauges were read out. Static pressure in the air system and exhaust gases system was measured by U-tubes filled with water. Air temperature at boiler inlet and temperature of exhaust gases after the boiler was measured using

NiCr-Ni thermocouple with TESTO-925 measuring gauge. Content of O_2, CO and NO_x in exhaust gases after the boiler was measured using TESTO 3421 and TESTO 342.3 computer measuring kid. During measurements, samples of coal from a feeding screw, samples of slag from a scraper under the boiler, samples of fly ashes from underneath of electrofilter as well as samples of blast-furnace and coke gases from the pipeline supplying the boiler, were taken for chemical analysis.

Gas sample from the pipeline was taken according to the BN-75/0540-02 Polish standard. To get a mean sample, the gas portions were collected during the measurement duration to a suction apparatus filled with saturated solution of sodium chloride. Additionally the gas sample was taken to a gas pipette. Analysis of the gas content was made in Laboratory of Department of Chemical Organic Technology and Petrochemistry in Silesian University of Technology in Gliwice. The analysis was made using gas chromatography with SRI 8610 C and INCO GC-505 gas chromatographs with three separate analytical columns and two separate TCD detectors and one FID detector. Standard sample of the content similar to the content of the tested gases was used for calculations.

Gas calorific value and its density was calculated on the basis of gas content according to DIN 51850 standard. Gross boiler efficiency was determined by an indirect method according to DIN 1942 standard assuming:

- reference temperature — 25 °C,
- coefficient of ash contraction — 10%,
- slag temperature at boiler outlet — 700 °C,
- coal temperature at boiler inlet — equal to air temperature at boiler outlet,
- distribution of ash that is in coal between slag, and fly ashes — respectively 10% and 90%.

DIN 1942 standard, according which the boiler measurements were taken, accepts such distribution ratio for calculations. Polish PN-72/M-34128 standard also accepts such a solution saying that for calculation the distribution respectively 15% and 85%, can be used. However, due to high share of burnt gas, i.e. higher flow speed in the heart chamber and higher dust load as well as on the basis of our previous experience, the above mentioned distribution ratio was accepted. Gas volume that was fed to burners was accepted on the level taken from the operational parameters for the real gas parameters (pressure and temperature).

4 Determined characteristics and the method of their validation

4.1 Determined characteristics

Structural parameters for each assumed function of the testing object characteristics were assessed on the basis of results obtained from the boiler balance measurements. Least squares method was used for their determination. Due to explanatory variables the estimation of non-linear model consists in a transformation leading to the linear form [2,3,13]. Obtained results were given in Tab. 2.

Table 2. Structural parameters of testing object functions.

Item	Coefficient symbol	Coefficients values						
		Boiler power efficiency	CO emission	CO_2 emission	NOx emission	SO_2 emission	Dust emission	Stream of coal chemical energy
		[–]	[kg/h]	[t/h]	[kg/h]	[kg/h]	[kg/h]	[MW]
1	b_0	0.4921	-29.4104	55.9940	704.0909	594.7726	225.0827	-31.5757
2	b_1	0.0034	-0.0353	-0.4495	-7.5309	-0.7531	-1.2111	-0.4031
3	b_2	-0.0008	-0.0609	0.0074	-3.1310	-1.4878	-0.2371	-1.4656
4	b_3	0.0021	0.1297	-0.0752	4.5957	-2.4413	-0.3739	3.1522
5	b_4	0.0044	1.6929	-0.4681	9.6574	-6.3088	-3.1541	7.3328
6	b_{11}	0.0000	0.0017	0.0006	0.0309	-0.0141	-0.0016	0.0097
7	b_{22}	0.0000	0.0003	0.0000	0.0011	-0.0003	0.0000	0.0008
8	b_{33}	0.0000	0.0000	0.0001	-0.0044	0.0018	-0.0001	-0.0036
9	b_{44}	0.0000	-0.0019	-0.0025	0.0849	-0.0222	-0.0146	0.0305
10	b_{12}	0.0000	-0.0007	0.0002	0.0086	0.0124	0.0027	0.0029
11	b_{13}	0.0000	0.0001	0.0000	-0.0024	0.0076	-0.0005	-0.0037
12	b_{14}	0.0000	-0.0089	0.0040	-0.0922	0.0569	0.0274	-0.0553
13	b_{23}	0.0000	0.0002	0.0000	-0.0015	0.0010	0.0004	-0.0010
14	b_{24}	0.0000	0.0006	-0.0007	0.0173	-0.0149	-0.0046	0.0092
15	b_{34}	0.0000	-0.0033	0.0015	-0.0707	0.0097	0.0080	-0.0376

4.2 Verification of obtained characteristics

etermined functions of the object were verified to check if estimated functions describe tested correlation good enough. The verification consisted in checking conformity of the model with measurements data by [3,15]:

- comparison of calculated values with the measurement data,
- determination of variance of residual component and determination of coefficient of random variable,
- defining the determination coefficient and coefficient of multiple correlation.

Besides assessment of structural parameters was performed by:

- determination of standard errors in assessment of structural parameters,
- carrying out test of significance of estimated structural parameters.

Information concerning values of indexes determined during verification of obtained characteristics was given in Tab. 3.

Table 3. Values of determined indexes.

Parameter determined by the characteristics	Parameter qualifying calculation conformity with the measurements			
	Se^2	ν_e	R^2	R
boiler efficiency	0.0005	0.02	0.87	0.93
coal chemical energy stream	343.4421	100.72	0.94	0.97
CO emission	2.5543	5.24	0.97	0.98
CO_2emission	0.3224	4.00	0.92	0.96
NOx emission	2947.4647	143.85	0.89	0.94
SO_2emission	868.5175	119.23	0.84	0.92
dust emission	17.0916	12.48	0.92	0.96

Variance of residual component as well as errors in assessment of structural parameters give the information about assessment of model conformity with empirical data. Variance of residual component was determined according to the following formula [15]:

$$s_e^2 = \frac{\sum e_t^2}{n-k-1}\ , \tag{9}$$

where:
n – number of observations (19),
k – number of independent variables (14),
e – residual component.

Variance of residual component for each testing object functions as well as standard deviation result from the formula:

$$s_e = \sqrt{s_e^2}\ . \tag{10}$$

Degree of matching of determined object functions can also be assessed by the coefficient of random variability, a measure based on standard deviation of residuals:

$$\nu_e = \frac{s_e}{\overline{y}}\ , \tag{11}$$

where $\overline{y}$ is the mean value of output dependent variable.

Obtained information shows what percentage of mean arithmetic value of response variable of testing object functions makes the standard deviation of residuals.

Verification was also carried out using determination coefficient R^2 that determines to what degree the testing object functions have been explained by variables describing the object [8].

$$R^2 = \frac{\sum_{t=1}^{n} (\hat{y}_t - \bar{y})^2}{\sum_{t=1}^{n} (y_t - \bar{y})^2}\ , \tag{12}$$

where $\hat{y}_t$ is value of y calculated from the model, referring to t-th system of independent variables. The higher is R^2 (range [0;1]), the model is better explained by variables describing it.

The following coefficient of multiple correlation proves the strength of correlation between response variable and all explanatory variables of the model:

$$R = \sqrt{R^2}\ . \tag{13}$$

As the value of that coefficient is within the range [0,1], the value approaching oneness proves very strong correlation between response variable and explanatory variables. Obtained values of coefficient R^2 and R show that the developed models are explained with good accuracy by the variables that describe them. High values of determination coefficient, calculated for each model, give evidence of that. Information, obtained in a result of calculation of multiple correlation coefficient, indicates for the fact that between determined output dependent values (response variables) and input independent values (explanatory variables) there is a very strong correlation.

Verification of models with the use of statistical tests, proved conformity of developed models to the measurement data. Testing the quality of structural parameters assessment was the next stage of verification of properties of developed models. Using variance matrix and co-variance of structural parameters assessment the standard errors of structural parameters assessment were calculated [19]:

$$\mathbf{D}^2(\mathbf{b}) \ = s_e^2(\mathbf{Y}^T\mathbf{Y})^{-1} \ . \tag{14}$$

On the matrix diagonal the estimator variances were found.

During verification of estimated functions of the testing object the hypothesis of significance of structural parameters was made [3–5,9]:

$$H_0 : [\alpha_n = 0] \ , \tag{15}$$

assuming, that structural parameter is not significant against alternative hypothesis:

$$H_1 : [\alpha_n \neq 0] \ , \tag{16}$$

assuming, that structural parameter is significant. The following statistics is a proof of this hypothesis:

$$b_n : I_n = \frac{|b_n|}{s\,(b_n)} \ . \tag{17}$$

Critical value b_α taken from t-Student distribution for $n-k-1$ degrees of freedom and significance level $\alpha = 0.05$ for the estimated functions is 2.7764 [13]. By comparison of critical value with the values determined by formula (17) it was found that in all cases in which the value:

$$I_n > b_\alpha \ , \tag{18}$$

H_0 hypothesis should be excluded, what means that each structural parameter, for which inequality (18) is fulfilled, is not statistically significant. In the specified models, H_0 hypothesis, saying about no significance of structural parameters, was excluded for the majority of parameters.

Estimated structural parameters of the function give evidence of their good matching. Calculated values, determined on the basis of each function, slightly differ from the measurement data.

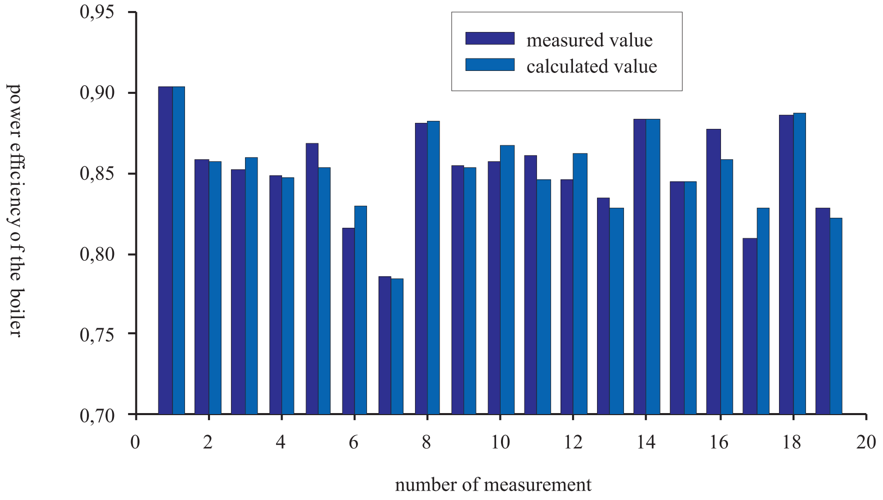

Figure 2. Exemplary comparison of values calculated from the model of boiler power efficiency with the measurement data.

5 Summary

Power and ecological characteristics of OPG-230 boiler was determined basing on 19 balance measurements, carried out according to the developed experimental design. Obtained calculation results were statistically assessed and the correlation between tested variables was found.

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Charakterystyki energetyczne i ekologiczne kotła buforowego zasilanego węglem i gazami poprocesowymi

Streszczenie

Celem opracowania jest przedstawienie sposobu wyznaczania charakterystyk energetycznych i ekologicznych kotła parowego, przystosowanego do buforowego spalania pyłu węglowego oraz gazowych paliw odpadowych, takich jak gaz wielkopiecowy, konwertorowy i koksowniczy. Przez charakterystykę rozumie się zależność analizowanego parametru energetycznego (np. sprawności lub strumienia energii chemicznej węgla kamiennego) lub ekologicznego (emisji substancji szkodliwych) od strumieni energii chemicznej poszczególnych gazów odpadowych oraz wydajności kotła. Charakterystyki energetyczne mogą być stosowane przy określaniu efektów działania kotłów przy zmiennych warunkach eksploatacji.