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Mathematical model of a steam boiler as a control plant

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ABSTRACT

The article highlights the problems associated with unpredictable outages, uncertainties in fuel supply, unpredictable changes in coal quality, and deterioration of the infrastructure of a thermal coal-fired power plant due to the use of high-ash fuels. Traditional methods of solving these problems lack adaptability and flexibility. The aim of the study was to improve the efficiency of operation of boiler units of thermal coal-fired power plants, which consists in increasing the service life, by improving the models of thermal coal quality management under random perturbations of its composition using automated measurement of abrasive materials in the dust removal system in real time. A simulation model of the influence of coal quality on the erosion wear of heat exchange surfaces of a steam boiler of a thermal coal-fired power plant was developed, consisting of a model of coal transportation and supply, a model of coal quality control, and a model of coal abrasiveness. The models were validated using a computerized flotation test comparison experiment and a one-factor analysis of variance. The experimental results showed that the group mean errors generally do not differ significantly. A method was also developed for controlling the quality of combusted coal when the abrasive composition of the coal batch formed by the supplier is disturbed. The proposed models and methods have the potential to significantly improve the efficiency of thermal coal-fired power plants through the use of computer-integrated systems for managing pipe wear resistance and reducing the need for premature repair and replacement of equipment, as well as ensuring satisfactory quality of fuel and abrasive compositions, namely, fixing the service life of pipes within 5-9 years, as opposed to the unconscious use of highly abrasive fuel, which will cause an urgent shutdown of a thermal coal-fired power plant within a year. This study opens the way to improving the operation of a thermal coal-fired power plant and expands the understanding of the relationship between coal quality and equipment wear. However, further empirical studies with a larger data set would be useful to improve the accuracy and versatility of the model.

Keywords: Thermal power plants; coal quality; supplier selection; cochrane sampling formula; computer-integrated control system; automated control system; automatic control methods

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INTRODUCTION

The challenges faced by Ukraine's energy system in the context of war require immediate solutions. The need for an in-depth analysis of the situation and the development of effective strategies for the restoration and further operation of energy facilities is more urgent than ever. The need to use computer technology to model situations, predict and solve problems is undeniable. Exhausted by missile strikes, these facilities are experiencing increasing difficulties that could lead to their unpredictable shutdown. This, in turn, could lead to critical infrastructure disruptions, given the country's heavy dependence on reliable energy supplies. In addition to direct losses, there is a risk of unexpected breakdown of power units, which may require their shutdown for diagnosis, identification of the problem and repair. In such circumstances, the time to restore the plant's operation is critical, and the hostilities only increase this risk.

Along with these problems, supplying fuel for thermal power plants in a time of war also becomes a much more difficult task. Coal, as the main fuel for many thermal power plants, requires a constant and reliable supply, which is impossible in wartime. Research into fuel quality, its erosive effect on equipment, and the difficulty of delivery becomes a priority.

LITERATURE REVIEW

Changes in coal quality have a significant impact on the performance of coal-fired power units. The efficiency of these units decreases when coal quality deteriorates, with carbon, ash and moisture content is the dominant factor. Dynamic processes associated with such changes can lead to fluctuations in thermal parameters, increased energy consumption, and problems with matching power output to load commands. To counteract this, a modified control method [1] for the water-fuel mixture (WFM) was proposed, which incorporates coal quality variations into the WFM calculation. This strategy made it possible to improve the performance of the thermal system by reducing fluctuations in thermal parameters and increasing the efficiency of the power unit.

Studies [2, 3] have shown that many of these accepted approaches are either outdated or lack the flexible adaptability needed to cope with dynamic high-pressure situations, particularly in war conditions, when there may be a sudden shortage of fuel or an immediate and urgent need for control actions to counteract or mitigate potentially damaging effects on thermal power plant (TPP) equipment.

Some of the procedures and methods described in [4, 5], [6, 7], although based on modern technologies, require the purchase and operation of very expensive specialized equipment. These modern technologies, while theoretically superior, pose significant logistical and financial challenges, increasing both the monetary investment and the time required to potentially unmanageable proportions.

A notable factor contributing to the wear and tear of TPP infrastructure is the combustion of high-ash fuels. High-ash fuels, especially if they are contaminated with abrasive impurities, contribute significantly to the gradual erosion of the surface of heat exchanger tubes. The interaction of such contaminated fuel with flue gases during combustion leads to a constant deterioration of these critical components of the TPP infrastructure. This phenomenon, combined with the shortcomings of existing monitoring and control methods, emphasizes the complexity and severity of the problems associated with ensuring the durability of heat exchanger tubes at TPPs.

Wear associated with the process of burning abrasive fuels is a well-known phenomenon described in detail in [8, 9]. This causes gradual and continuous erosion of the surface of heat exchangers at TPPs. Existing methods of coal quality control, such as the detailed sampling method presented in [10], are labour-intensive and not adaptive enough. These procedures require continuous evaluation of each batch of coal and individual determination of the sampling step, which, given the constant arrival of mixed coal supplies from different sources, can lead to significant delays in transportation. These delays also lead to significant costs for TPPs due to excessive railcar maintenance. Since the existing methods for predicting the consumption of different fuels, detection of fly ash in ash traps and abrasiveness do not effectively take into account the real-time operation time of the boiler tubes, a general mathematical model based on the new TPP steam boiler scheme has not yet been developed. The mathematical model should combine arguments that take into account different types of fuel consumption, fly ash in ash collectors, and abrasiveness with functions. These functions should describe the consumption of the total amount of ash and slag pulp, carbon losses due to the discrepancy between the declared and actual ash content of the parameter and take into account the discrepancy between the declared and actual ash content, as well as the duration of operation before maintenance.

Works [9] and [10] discuss various methods for determining the ash content of fuel during sampling. However, these procedures are labour-intensive, which creates difficulties during continuous fuel use. The need to burn available fuel before laboratory analysis results are available can lead to high ash content or, in our context, high abrasive content bypassing control measures. This unnoticeable surge of abrasive impurities in the coal stream can inevitably lead to abrasive wear of the boiler unit's heat exchange surface tubes. Existing methods of providing TPPs with high-quality coal are insufficient to reduce the abrasive impact on steam generator tubes. These methods need to be improved by integrating the possibility of adjusting the selection pitch. Such regulation will allow timely refusal of viscosity fuel and control of heat exchange tubes worn in TPP steam generators.

Numerous studies [1], [11, 12], [13] describe in detail the methods of measuring pipe thickness using acoustic or spectral sensors designed to prevent pipe erosion and facilitate timely replacement. Unfortunately, these methods require a complete shutdown of the power unit to perform the measurements. Outside of scheduled shutdown periods for pipe inspection, a severe drop in water pressure in the pipes may be the only harbinger of an impending failure and prompt an immediate shutdown to avoid a TPP accident that could seriously disrupt the power system. There is no understanding of the impact of changes in coal quality on the wear resistance of heat exchanger tubes of a TPP steam boiler without shutting down the power unit for inspection. There is also no dynamic quality control model. Existing dynamic models need to be improved and should include a coal transportation model, a coal quality control model, and a coal abrasiveness model, as well as a sampling rule to identify and control poor-quality fuel sources.

THE PURPOSE OF THE ARTICLE

The purpose of the article is to develop a mathematical model that will increase the efficiency of using heat exchange surfaces of a steam boiler of a thermal power plant, namely, to increase its service life, by improving methods for controlling the quality of coal that is burned under random perturbations of its composition by measuring the abrasive component in the dust removal system in real-time.

To achieve this goal, it is necessary to:

– To develop a simulation model of the influence of coal quality on the erosion wear of heat exchange surfaces of a steam boiler at a thermal power plant, which consists of a model of coal transportation and supply, a model of coal quality in terms of supply from different sources, and a model of the state of coal abrasiveness.

– Check the model for adequacy.

To develop a method for controlling the quality of combusted coal when the abrasive composition of the coal batch formed by the supplier is disturbed in order to reduce the erosion wear of the heat exchange surfaces of the steam boiler.

MAIN PART

1. MODELS OF COAL QUALITY INFLUENCE ON EROSION WEAR OF STEAM BOILER HEAT EXCHANGE TUBES

In [14], the objective function $Z(W, L, C) \rightarrow min$ was described. To build a mathematical model and check its adequacy, we first need to consider a schematic representation of this model. The general structure of the model is shown in Fig. 1.

The mathematical model ZTPP (1) was built in the form of a system of algebraic equations that reflect the daily cash costs of TPPs associated with forced premature repair and replacement of equipment, fuel enrichment, and other costs that need to be minimized;

$$ZTPP = \begin{cases} W = W_{enrich}(Ad, V_{purch}) \\ L = L_{log}(x, V_{purch}) \\ C = C_{TPP}(Ad, T_{equip}) \\ T = T_{equip}(Ad, V_{purch}) \\ V = V_{purch}\ (Ad) \end{cases} ; \qquad (1)$$

where W_{enrich} (Ad, V_{purch}) is a function that describes the costs associated with the fuel enrichment process, depending on Ad and the purchase volume V_{purch}; L_{log} (x, V_{purch}) is a function that describes the costs associated with logistics, depending on the purchase volume V_{purch}; V_{purch} (Ad) is a function for determining the required volume for purchase, taking into account the abrasiveness of the fuel.

C_{TPP} (Ad, T_{equip}) is a function that describes the costs of TPPs associated with environmental pollution, repair and replacement of equipment due to the use of highly abrasive fuel, depending on the operating time before an urgent shutdown for repair; T_{equip} (Ad, V_{purch}) is a function for calculating the time of current operation before repair.

Also, [15] described the principles of ash accumulation during combustion and the principles of ash and slag removal. This will help to develop a **subsystem for measuring coal abrasiveness (*Cad*)** of coal abrasiveness by measuring the deposition of abrasive coal material in the fuel combustion system to determine the actual abrasiveness of the fuel due to combustion;

The ash from the collectors is mixed with the furnace ash to form a sludge that is transported to the ash dump. By measuring the sludge flow and subtracting the process fluid, discrepancies between the actual and declared ash content can be detected. To solve the problem of abrasive damage caused by the accumulation of fly ash in the collectors, a flow meter in the collector pipes was proposed.

Taking into account the transportation delay and the density of the process fluid, it is possible to calculate the actual ash content (Fig. 2.) and its impact on the wear resistance of boiler equipment. Such a solution for determining fuel abrasiveness requires minimal additional equipment. The next step is to create a scheme for controlling the consumption of abrasive material.

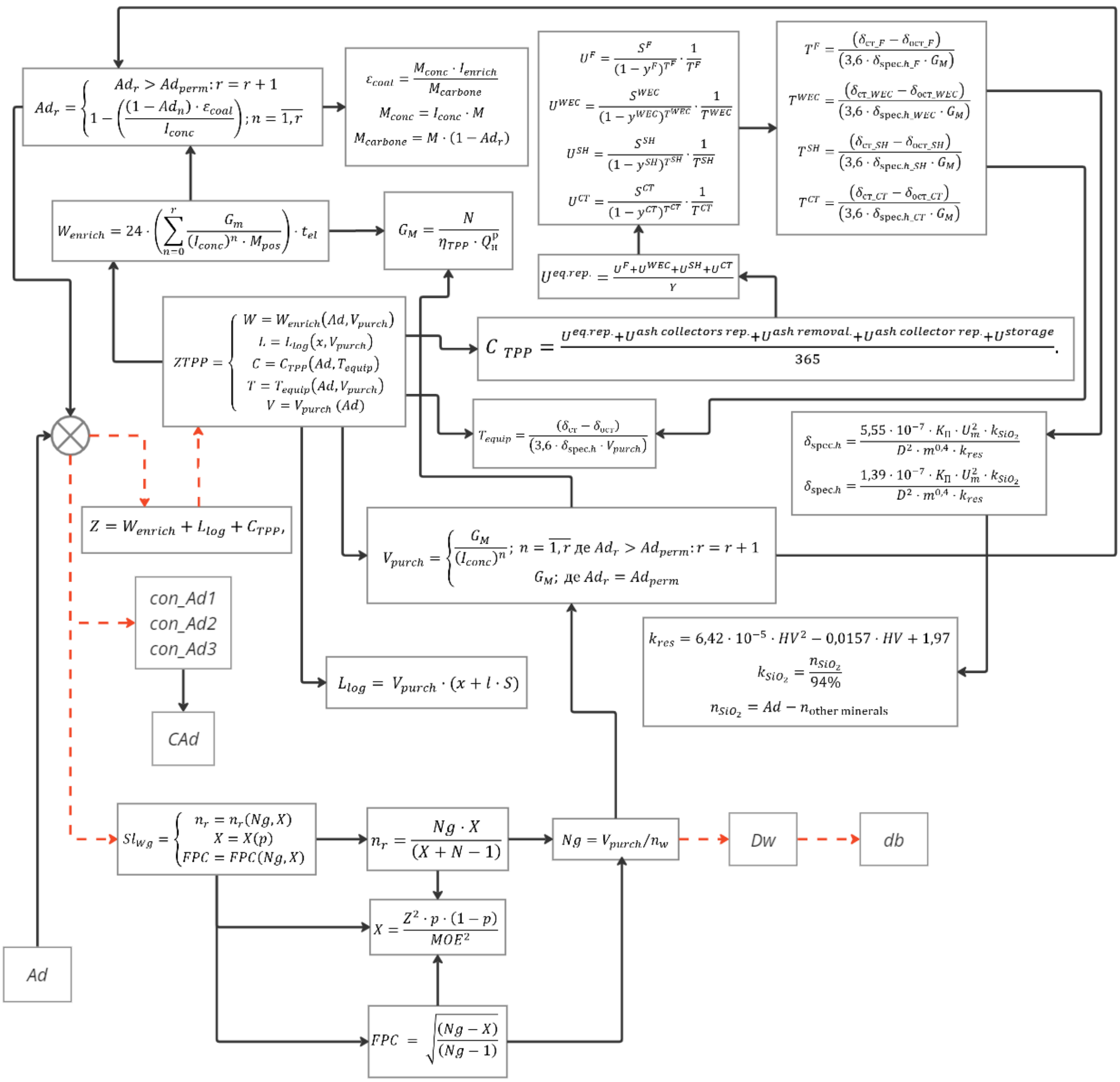

Fig. 1. **Structure of the model of coal quality influence on erosion wear of heat exchange tubes of a steam boiler**

Source: **compiled by the authors**

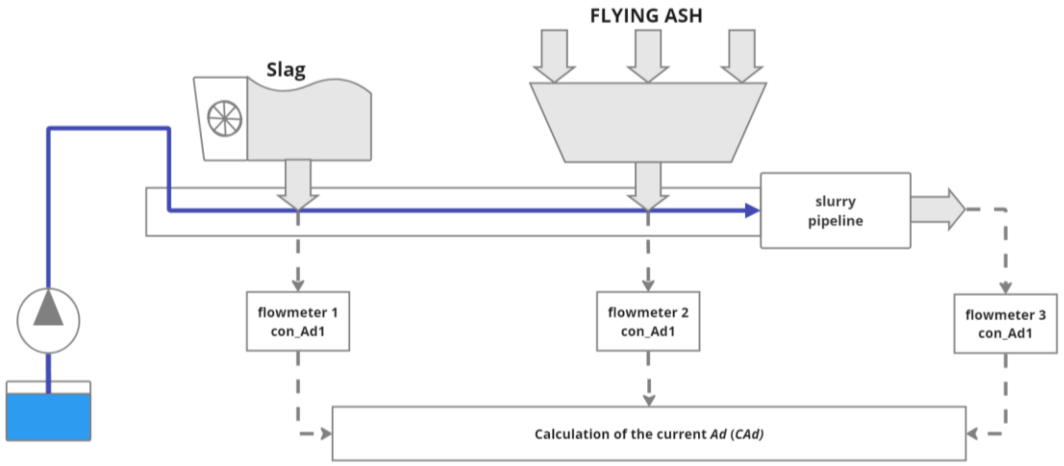

Fig. 2. **Complex for measuring the abrasiveness of coal**

Source: **compiled by the authors**

Finally, a **mathematical model Sl_{wg}** (2) for coal quality control was also suggested, it's in the form of a system of algebraic equations that reflects the formation of the sample size for checking the quality of coal, using the information from papers [15], [16, 17] and [18]:

$$Sl_{Wg} = \begin{cases} n_r = n_r(Ng, X) \\ X = X(p) \\ FPC = FPC(Ng, X) \end{cases}; \qquad (2)$$

where n_r is the sample size; *Ng* is the size of the general population, which is equal to $Ng = V_{purch}/n_w$, where n_w is the specific load of a railroad car; *X* is the sample size (calculated before *FPC*); *p* is the expected probability of leakage of low-quality fuel; *FPC* is the limited population correction.

2. CHECKING THE MODEL FOR ADEQUACY

The *ZTPP* model needs to be checked for adequacy. For this purpose, we considered the results of flotation tests [19] and [20] for steam coal, in particular, the display of graphs of compliance with the *Ad* (Ash content, %) of tailings during beneficiation relative to the proportion of tailings to fuel (Concentrate yield, %) under various conditions.

Table 1 and Fig. 3 show the results of coal enrichment with the MFU-25 equipment for six tons of fuel with an initial ash content of 44.8 %, where one iteration takes 1 hour.

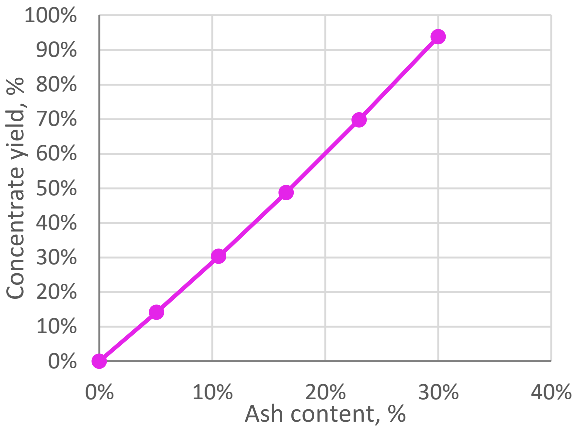

Fig. 3. **Graph of Concentrate yield versus Ash content**
Source: **compiled by the authors**

Initially, the study [19] was considered for comparison. In this study, an XFDII 1.0-L machine (Jianfeng Mill, Nanchang, China) was used as the beneficiation equipment for the laboratory flotation cell. In this study, the beneficiation scheme was described, where the amount of fuel was 80 g, where one iteration takes 30 seconds, and the release curves of high-ash fine coal for different media filling rates at an initial *Ad* of 42 % to 47.6 % were depicted. To verify the adequacy of the model, progressive release flotation curves for the crushed products with the best and worst-case scenarios were selected for comparison.

Table 2 shows a comparison of the results of matching the Yields % to the different *Ad* Yields for the XFDII 1.0-L. Fig. 4 illustrates this comparison.

Table 1. **Experimental results for the MFU-25**

r	***M, t***	***M_{carbon}, t***	***1-Ad, %***	***M_{ash}, m***	***Ad, %***	***Ad yields, %***	***Yields, %***	***M_{yields}, t***
0	6.00	3.31	55.20	2.69	44.80	0	0	0.00
1	5.26	3.15	59.86	4.66	40.14	5	14	0.74
2	4.60	2.99	64.92	3.96	35.08	10	30	1.40
3	4.03	2.84	70.40	3.33	29.60	15	49	1.97
4	3.53	2.70	76.35	2.77	23.65	21	70	2.47
5	3.10	2.56	82.80	2.27	17.20	28	94	2.90

Source: **compiled by the authors**

Table 2. **Comparison of experimental results for the MFU-25 and XFDII 1.0-L**

		XFDII 1.0-L (1)	MFU -25(1)		XFDII 1.0-L (2)	MFU -25(2)
i	***Ad yields, %***	***Yields, %***	***Yields, % (*)***	***Ad yields, %***	***Yields, %***	***Yields, % (*)***
1	**9.50**	18.00	28.50	**10.50**	12.50	30.50
2	**12.00**	24.50	35.00	**12.50**	35.00	37.50
3	**14.00**	37.50	43.00	**13.75**	49.00	41.00
4	**18.50**	60.50	58.50	**18.25**	58.00	58.00
5	**30.63**	100.00	94.00	**31.88**	100.00	98.00

Source: **compiled by the authors**

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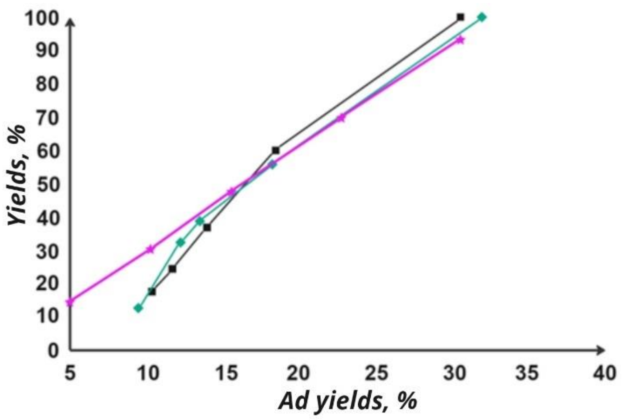

Fig. 4. **The graphical results are shown in Table 2**
***Source:* compiled by the authors**

We also reviewed [20], which describes the correspondence between *Ad* Yield % and Yield % under different operating times. The study was formulated for a more general case, so the enrichment equipment was not described (N/A). Similarly to Table 2, we considered the limit scenarios for comparison with the current model. The results are shown in Table 3 and Fig. 5.

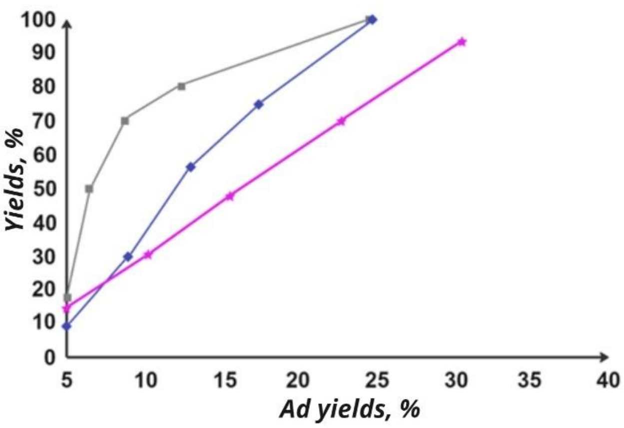

Fig. 5. **The graphical results shown in Table 3**
***Source:* compiled by the authors**

The following formulas were used to calculate the relative error:

$$\delta_i = \frac{Y_i^{\text{МФУ}} - Y_i^{\text{XFDII}}}{Y_i^{\text{XFDII}}} , \quad (3)$$

$$\delta_i = \frac{Y_i^{\text{МФУ}} - Y_i^{\text{N/A}}}{Y_i^{\text{N/A}}} , \quad (4)$$

where $Y_i^{\text{МФУ}}$ is the result of Yield % for the corresponding i for MFU-25; Y_i^{XFDII} / $Y_i^{\text{N/A}}$ is the result of the Yield % for the corresponding i for XFDII 1.0-L and N/A.

The results of the error calculation are shown in Table 4. The average relative error was calculated according to the formula:

$$\bar{\delta} = \frac{1}{n} \sum_{j=1}^{n} \delta_j \quad (5)$$

From Table 4, we can obtain the average relative error $\bar{\delta}$ = - 0.00316.

Also, to test the adequacy of the model, a one-factor analysis of variance (ANOVA) was conducted. For the input matrix data, we took the values of the relative error under different conditions (Table 5), where $\delta_{i.cp.}$ are the group averages.

The scatter of group averages of the failure rate relative to the overall average is affected by both changes in the level of the factor in question and random factors.

In order to take into account the influence of this factor, the total sample variance was divided into two parts, the first of which is (factor) S_{2f}, and the second is (residual) S_{2res}. In order to account for these components, we first calculated the total sum of the squared deviations of the variants from the overall mean (S_t).

$$S_t = \sum\sum(\delta_{ij}^2 - \bar{\delta}^2) , \quad (6)$$

the factor sum of the squared deviations of the group means from the overall mean, which characterizes the influence of this factor:

$$S_{\text{F}} = 5 \cdot \sum(\delta_j^2 - \bar{\delta}^2) , \quad (7)$$

which is obtained by replacing each variant in the S_t expression with the group mean for that factor.

Table 3. **Comparison of the experimental results for N/A and MFU-25**

		N/A (1)	MFU-25(1)		N/A (2)	MFU-25(2)
i	***Ad yields, %***	***Yields, %***	***Yields, % (*)***	***Ad yields, %***	***Yields, %***	***Yields, % (*)***
1	**5.00**	18.00	15,00	**5.00**	9.00	15.00
2	**6.30**	50.00	19,60	**8.30**	30.00	26.00
3	**8.75**	70.20	27,00	**13.00**	57.50	39.50
4	**12.70**	80.00	38,00	**13.00**	56.50	40.00
5	**24.25**	100.00	76,00	**24.90**	100.00	77.00

***Source:* compiled by the authors**

Table 4. **Calculating the relative error under different conditions**

j	*δ*	*i*	*Equipment*	*j*	*δ*	*i*	*Equipment*
1	0.58	1	XFDII 1.0-L (1) | MFU-25 (1)	11	-0.17	1	N/A (1) | MFU-25(1)
2	0.43	2	XFDII 1.0-L (1) | MFU-25(1)	12	-0.61	2	N/A (1) | MFU-25(1)
3	0.15	3	XFDII 1.0-L (1) | MFU-25(1)	13	-0.62	3	N/A (1) | MFU-25(1)
4	-0.03	4	XFDII 1.0-L (1) | MFU-25(1)	14	-0.53	4	N/A (1) | MFU-25(1)
5	-0.06	5	XFDII 1.0-L (1) | MFU-25(1)	15	-0.24	5	N/A (1) | MFU-25(1)
6	1.44	1	XFDII 1.0-L (2) | MFU-25(2)	16	0.67	1	N/A (2) | MFU-25(2)
7	0.07	2	XFDII 1.0-L (2) | MFU-25(2)	17	-0.13	2	N/A (2) | MFU-25(2)
8	-0.16	3	XFDII 1.0-L (2) | MFU-25(2)	18	-0.31	3	N/A (2) | MFU-25(2)
9	0.00	4	XFDII 1.0-L (2) | MFU-25(2)	19	-0.29	4	N/A (2) | MFU-25(2)
10	-0.02	5	XFDII 1.0-L (2) | MFU-25(2)	20	-0.23	5	N/A (2) | MFU-25(2)

Source: **compiled by the authors**

Table 5. **Input error data for a one-factor analysis of variance**

	XFDII 1.0-L		N/A	
No.	***δ₁***	***δ₂***	***δ₁***	***δ₂***
1	0.5833	1.44	-0.167	0.6667
2	0.4286	0.07143	-0.608	-0.133
3	0.1467	-0.1633	-0.615	-0.313
4	-0.033	0	-0.525	-0.292
5	-0.06	-0.02	-0.24	-0.23
$\boldsymbol{\delta_{i.cp.}}$	0.213	0.266	-0.431	-0.0603
Σ	1.0655	1.3281	-2.155	-0.3017

Source: **compiled by the authors**

The residual sum of squared deviations is obtained as a difference:

$$S_{\text{res}} = S_t - S_{\text{F}}\ , \tag{8}$$

to determine the total sample variance D_t, we used (9), and to obtain the unbiased total sample variance S_{2t}, we used (10):

$$D_t = \frac{S_t}{h \cdot k}\ , \tag{9}$$

$$S_{2\text{res}} = \frac{D_t}{h \cdot (k-1)}\ , \tag{10}$$

respectively, for the unbiased factor sample variance:

$$S_{2\text{f}} = \frac{S_{\text{F}}}{h-1}\ , \tag{11}$$

where *h-1* is the number of degrees of freedom of the unbiased factor sample variance of the factor.

In order to assess the influence of the factor on changes in the parameter under consideration, the value is calculated:

$$f_{\text{t}} = \frac{S_{2\text{f}}}{S_{2\text{res}}}\ . \tag{12}$$

Since the ratio of the two sample variances S_{2f} and S_{2res} is distributed according to the Fisher-Snedeker law, the resulting value of f_t is compared with the value of the distribution function at the critical point f_{cr}, which corresponds to the selected significance level α. If $f_t > f_{cr}$, then the factor has a significant impact and should be taken into account, otherwise it has a minor impact that can be neglected.

If the mean values of a random variable calculated from separate samples are the same, then the estimates of the factor and residual variances are unbiased estimates of the general variance and differ only slightly. In this case, a comparison of the estimates of these variances by Fisher's criterion should show that there is no reason to reject the null hypothesis that the factor and residual variances are equal. The estimate of the factor variance is greater than the estimate of the residual variance, so we can immediately assert the injustice of the null hypothesis of equality of mathematical expectations across sample layers

In this case, *h* and *k* are 4 and 5, respectively. Using the table of squares (Table 6), we can find the necessary indicators.

Table 6. **Tables of squared error values**

	XFDII 1.0-L		N/A	
No.	***δ11^2***	***δ12^2***	***δ21^2***	***δ22^2***
1	0.34028	2.07360	0.02778	0.44444
2	0.18367	0.00510	0.36966	0.01778
3	0.02151	0.02666	0.37870	0.09800
4	0.00109	0	0.27563	0.08528
5	0.00360	0.00040	0.05760	0.05290
Σ	0.55016	2.10576	1.10937	0.69840

Source: **compiled by the authors**

Using (6)-(8), it was obtained: $S_t = 4.46$; $S_F = 1.53$ and $S_{зал} = 2.94$. Using (10) and (11), the factor and residual variances were calculated: $S_{2f} = 0.51$; $S_{2res} = 0.18$.

In this example, the factor F has a significant impact on the random variable. The null hypothesis H_0 was tested: equality of mean values of x.

From (12) it was obtained $f_t = 2.83$. For the significance level $\alpha = 0.05$, the number of degrees of freedom 3 and 16, $f_{cr} = 3.24$ (from the Fisher–Snedecor distribution table)

Due to the fact that $f_t < f_{cr}$, the null hypothesis about the significant influence of the factor on the results of the experiments was rejected (the null hypothesis about the equality of group means was accepted). In other words, the group mean errors, in general, do not differ significantly.

Finally, the following error results were presented:

To conclude, the following error results were presented:

– maximum relative error $\delta_{max} = 1.44$;

– minimum relative error $\delta_{min} = -0.62$;

– average relative error $\bar{\delta} = -0.00316$.

3. METHODS FOR CONTROLLING THE EFFICIENCY OF COAL PREPARATION FOR COMBUSTION

A structural method is proposed to create a method for controlling the condition of pipes of the heat exchange surface of a steam boiler of a TPP. The structure of the integrated subsystem of coal preparation for combustion is shown in Fig. 6.

Special attention was paid to the fuel quality control method, which defines a systematic approach to coal quality control and reserve stock management using the *Slwg* model for the method. A representative sample from each batch of coal is selected for testing. If the quality of combustion falls below a predetermined level, the sampling frequency changes according to the conditions of the mathematical model, which ultimately leads to the inspection of each car, if necessary.

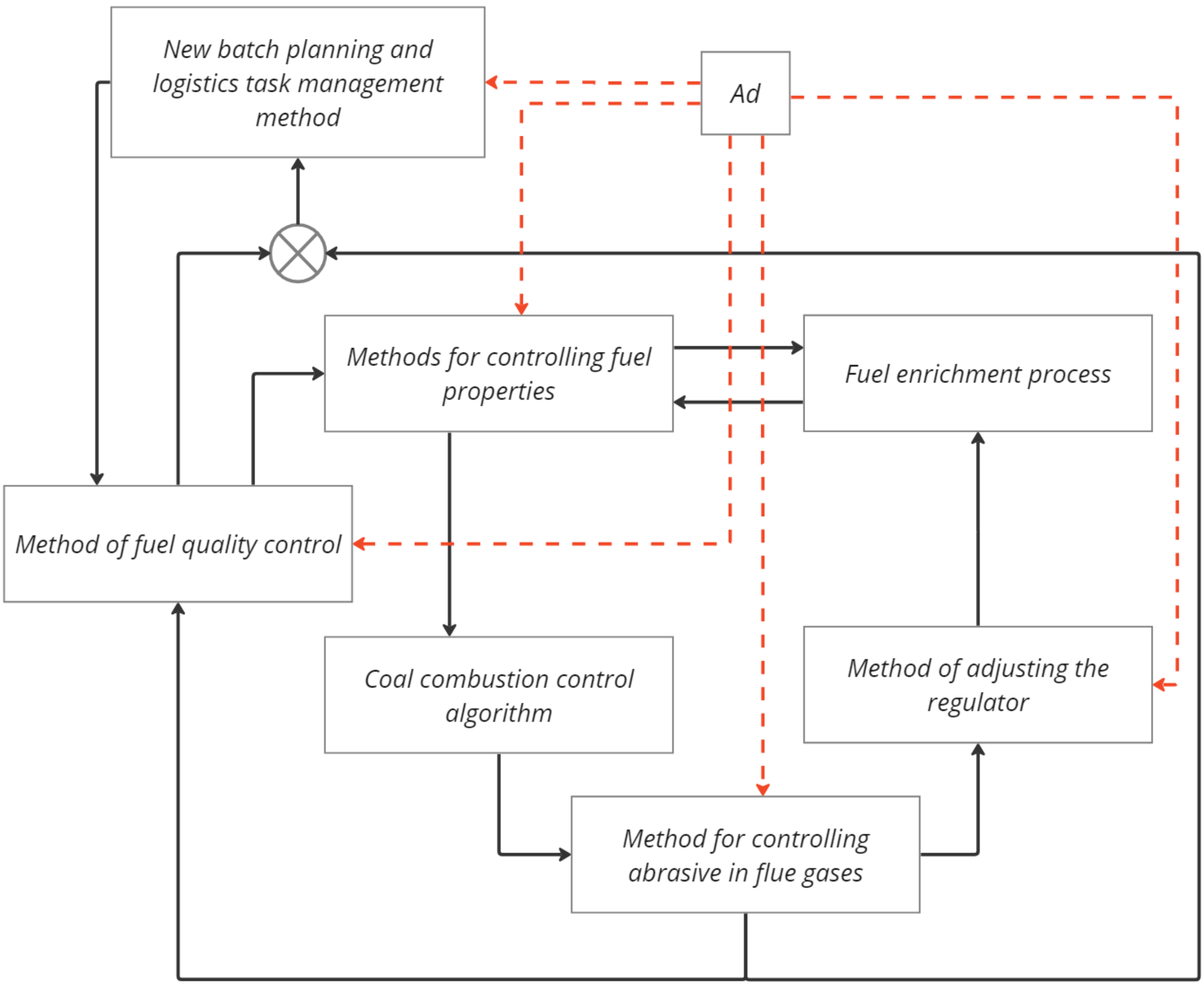

Fig. 6. **The structure of the integrated subsystem of coal preparation for combustion**
Source: **compiled by the authors**

The model also describes the unloading of coal depending on the results of the quality analysis and the need to replenish reserve stocks.

If the actual quality of coal is found to be below the specified quality, it is concluded that the sampling step does not provide sufficient verification. The sampling step is reduced according to the following rule formulated by the mathematical model (1). In [21], it is described that the most typical trains are those with the number of railcars from 28 to 42 (where the break-even point is 29), as can be seen in Fig. 7. To build the method, we considered the daily acceptance of 24 trains, each consisting of 35 railcars.

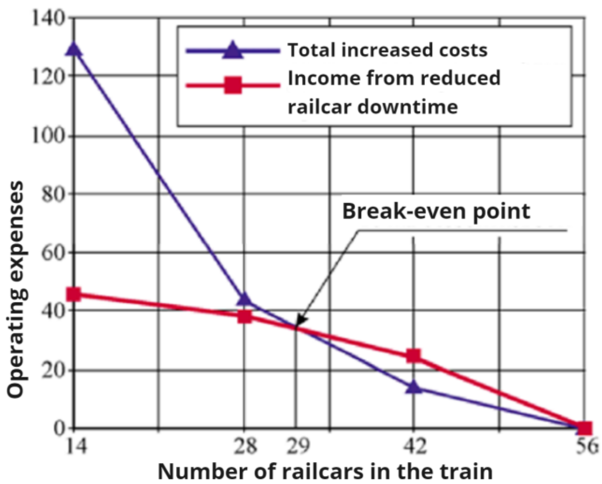

Fig. 7. **The number of railcars in the train and the corresponding operating costs**
Source: **The graph is taken and translated from [21]**

The sampling process can be seen in detail in Table 7 and Table 8.

Table 7. **Sampling recommendations for abrasiveness for satisfactory quality**

i	*Ad* *(0-15.99%)*	*r*
0	0	10
1	15.99	10
2	15.99	10
3	15.99	10
4	15.99	10

Source: **compiled by the authors**

The recommended initial sample size for inspection is $n_r = 85$ railcars, or about 10 % of the total number of railcars, with every 10th railcar inspected (inspection step $r = 10$). If the inspection proves to be ineffective, the proportion of expected defective railcars is increased to 15 %, and the new sample size is $n_r = 190$ railcars, or about 20 % of the total, with a check every 5th railcar ($r = 5$). If defective fuel is still entering the system, the expected fraction of defective railcars is increased to 50 % and the sample size is increased to $n_r = 470$ railcars, which is about 40 % of the total, with every 2nd railcar checked ($r = 2$). If this does not work, the last resort is to check every railroad car ($r = 1$), until a defective fuel is found. It can be seen that up to 16% abrasiveness, the sampling step remains at the standard level of $r = 10$, while any coal above 16 % abrasiveness causes a gradual decrease in the sampling step to the final $r = 1$.

Table 8. **Recommendations for sampling with respect to the abrasiveness index, for unsatisfactory quality**

i	*Ad* *(16-29,99%)*	*Ad* *(30-35%)*	*r*
0	16	30	10
1	30	35	10
2	30	35	5
3	30	35	2
4	30	35	1

Source: **compiled by the authors**

The experiment number in both graphs refers to each moment of detection of actual abrasion due to combustion, namely:
0 – previous fuel; 1 – start of combustion of the current fuel; 2 – detection of abrasive and reduction of the sampling step; 3 – repeated detection of abrasive and repeated reduction of the sampling step; 4 – reduction of the sampling step to $r = 1$, until the moment of detection of abrasive.

The method of controlling abrasive in flue gases was also described in detail, which describes the procedure for detecting and measuring abrasive (ash) during coal combustion at a thermal power plant. It involves monitoring the ash formation process using a special measuring channel and determining the ash content in ash and slag during pulp formation using a flow meter. A change in the current amount of solid fraction in the pulp compared to the previous period indicates a change in coal quality. We consider the classes of coal proposed in [22] (Table 9).

In Fig. 8, the decimal logarithms of the years of operation for a particular coal class were chosen as the ordinate axis. It can be seen that for the most typical coal class, “Normal”, the service life of the pipes before replacement ranges from 5 to 9 years.

Table 9. **Minimum and maximum operation of boiler tubes before repair or replacement for different coal classes**

Ad	*Coal classes*	*min, years*	*max, years*
0-5 %	Ideal	-	17.75
5-9 %	Good	17.69	9.43
9-16 %	Normal	9.42	4.89
16-30 %	Unsatisfied	4.89	2.17
30+ %	Bad	2.17	-

Source: **compiled by the authors**

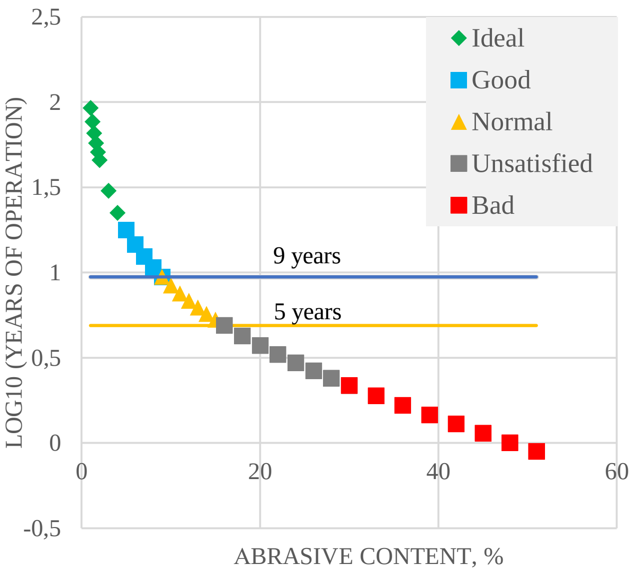

Fig. 8. **The service life of pipes for different classes of coal**

Source: **compiled by the authors**

CONCLUSIONS

1. Suggested models were validated using flotation tests and one-factor analysis of variance (ANOVA). The experimental results showed the ability of the models to correctly predict the erosion wear of heat exchange tubes under different conditions. The result is $f_t < f_{cr}$, which means that the group mean errors generally do not differ significantly. The errors themselves were obtained: $\delta_{max} = 1{,}44$; $\delta_{min} = -0{,}62$; $\bar{\delta} = -0{,}00316$

2. Implementation of an integrated subsystem of coal preparation for combustion to regulate the abrasive composition of the coal charge is important for extending the service life of the equipment. To this end, a systematic approach to coal quality control has been developed that takes into account the need to replenish reserve stocks and modify the sampling frequency based on combustion quality.

3. The models and methods proposed in this article have the potential to significantly improve the efficiency of TPPs by reducing the need for premature repair and replacement of equipment, as well as ensuring satisfactory quality of fuel and abrasive compositions, namely, to fix the service life of pipes within 5-9 years, as opposed to the unconscious use of highly abrasive fuel, which will cause an urgent shutdown of the TPP within 1 year. This study opens the way to improving TPP operations and expands the understanding of the relationship between coal quality and equipment wear. However, further empirical studies with a larger data set would be useful to improve the accuracy and versatility of the model.

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АНОТАЦІЯ

У статті висвітлено проблеми, пов'язані з непередбачуваними відключеннями, невизначеностями з постачанням палива, непередбачуваною зміною якості вугілля та зношеністю інфраструктури теплової вугільної електростанції через використання високозольних видів палива. Традиційним методам вирішення цих проблем бракує адаптивності та гнучкості. Мета дослідження полягала у підвищенні ефективності експлуатації котлоагрегатів теплових вугільних електростанцій, яка полягає у збільшенні терміну експлуатації, за рахунок вдосконалення моделей керування якістю енергетичного вугілля при випадкових збуреннях його складом за допомогою автоматизованого вимірювання абразивних матеріалів в системі пиловидалення в реальному часі. Було розроблено імітаційну модель впливу якості вугілля на ерозійний знос теплообмінних поверхонь парового котла теплової вугільної електростанції, яка складається з моделі транспортування та постачання вугілля, моделі контролю якості вугілля та моделі стану абразивності вугілля. Моделі були перевірені за допомогою комп’ютерного експерименту порівняння флотаційних випробувань та однофакторного дисперсійного аналізу. Експериментальні результати показали, що групові середні похибки загалом різняться не значимо. Також було розроблено метод керування якістю вугілля, що спалюється, при збуренні абразивним складом партії вугілля, яке формує постачальник. Запропоновані моделі та методи мають потенціал для значного підвищення ефективності роботи теплових вугільних електростанцій за рахунок використання комп’ютерно-інтегрованих систем керування зносостійкості труб і зменшення потреби в передчасному ремонті та заміні обладнання, а також забезпечення задовільної якості палива та абразивних складів, а саме зафіксувати термін експлуатації труб в межах 5-9 років, на відмінну від несвідомого використання високоабразивного палива, що викличе термінову зупинку теплової вугільної електростанції протягом 1 року. Це дослідження відкриває шлях до покращення роботи теплової вугільної електростанції і розширює розуміння взаємозв'язку між якістю вугілля та зносом обладнання. Однак подальші емпіричні дослідження з більшим набором даних були б корисними для підвищення точності та універсальності моделі.

Ключові слова: Теплові електростанції; якість вугілля; вибір постачальника; формула відбору проб Кокрана; комп’ютерно-інтегрована система керування; автоматизована система управління; методи автоматичного управління.

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