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MODELS AND METHODS FOR IMPROVING THE OPERATION OF THE ENERGY FACILITY CONTROL SYSTEM

П. Грішин, М. Грішин, К. Жанько. **Моделі та методи для покращення роботи системи керування енергетичним об'єктом.** Ця стаття присвячена вдосконаленню методів і моделей для комп'ютерно-інтегрованої системи управління (КІСУ), яка контролює знос теплообмінних поверхонь труб у парових котлах на вугільних теплових електростанціях (ТЕС), зокрема для вугілля з невідомим абразивним складом. Система використовує дані про якість вугілля в режимі реального часу для управління абразивом, оптимізації розподілу вугілля та перевірки якості вугілля з метою зниження витрат. Описано, що труднощі, з якими стикається світова вугільна промисловость, пов'язані із питаннями якості, ціни та екології, а перехід до сталої енергетики ускладнюється цим розмаїттям. Ефективне виробництво електроенергії залежить від точної ідентифікації складу палива та мінімізації пошкоджень від абразивних домішок палива теплообмінних труб. Незважаючи на існуючі аналітичні методи, існує потреба в удосконаленні технології діагностики, що передбачає інтеграцію автоматизованих систем для підвищення ефективності та сталості. Представлено математичну модель, яка розраховує вплив різних типів вугілля та домішок на знос теплообмінних труб, максимізуючи термін служби та мінімізуючи витрати. Вона включає в себе правило відбору проб Кокрана для покращення контролю якості вугілля. Також розроблено автоматизований метод управління якісю вугілля для зменшення зносу від абразивних вугільних домішок. Він включає в себе поетапний вибір постачальника і метод використання запасів, посилюючи контроль над зносом за допомогою методу покрокової вибірки Кокрана. Крім того, керуючий пристрій на основі нечіткої логіки розподіляє потік таким чином, щоб забезпечити задовільну якість вугілля, підкреслюючи необхідність безперервного моніторингу системи. Створено модельно-орієнтовану КІСУ, яка керує потоком вугілля на основі ідентифікації домішок у реальному часі, що призводить до значної економії коштів і збільшення міжремонтних інтервалів. Обчислювальні експерименти підтверджують, що КІСУ може більш ніж подвоїти термін служби теплообмінних труб за рахунок підтримання задовільної товщини, тим самим відтерміновуючи ремонти і знижуючи експлуатаційні витрати. В цілому, в статті представлено комплексний підхід до управління та оптимізації зносу теплообмінних труб на вугільних ТЕС з використанням моделювання, аналізу даних в реальному часі та автоматизованих систем управління для підвищення ефективності та стійкості.
Ключові слова: модельна система, спалювання, ідентифікація складу палива, комп'ютерна-автоматизована система, математична модель, барабанний парогенератор, контролер реального часу, система автоматичного управління, система нечіткого управління, оптимальний метод пошуку рішень

P. Hrishyn, M. Grishyn, K. Zhanko. **Models and methods for improving the operation of the energy facility control system.** This article is devoted to improving methods and models for a computer-integrated control system (CICS) that monitors the wear of heat exchange surfaces of pipes in steam boilers at coal-fired thermal power stations (TPP), in particular for coal with unknown abrasive composition. The system uses real-time coal quality data to 1manage the abrasive, optimize coal distribution, and verify coal quality to reduce costs. It is described that the difficulties faced by the global coal industry are related to quality, price and environmental issues, and the transition to sustainable energy is complicated by this diversity. Efficient power generation depends on accurate identification of fuel composition and minimizing damage from abrasive impurities in the fuel of heat exchangers. Despite the existing analytical methods, there is a need for improved diagnostic technology, which involves the integration of automated systems to improve efficiency and sustainability. The paper presents a mathematical model that calculates the effect of different types of coal and impurities on the wear of heat exchange tubes, maximizing service life and minimizing costs. It includes a Cochran sampling rule to improve coal quality control. An automated coal quality management method was also developed to reduce wear from abrasive coal impurities. It includes a stepwise supplier selection and stock utilization method, enhancing wear control using the Cochran stepwise sampling method. In addition, a fuzzy logic-based control device distributes the flow in such a way as to ensure satisfactory coal quality, emphasizing the need for continuous system monitoring. A model-based CICS has been developed that controls coal flow based on real-time impurity identification, resulting in significant cost savings and extended overhaul intervals. Computational experiments confirm that the CICS can more than double the service life of heat exchange tubes by maintaining a satisfactory thickness, thereby postponing repairs and reducing operating costs. Overall, this article presents a comprehensive approach to managing and optimizing heat exchanger tube wear at TPP using modelling, real-time data analysis, and automated control systems to improve efficiency and sustainability.
Keywords: model-based system, combustion, identification of fuel composition, computer-automated system, mathematical model, drum steam generator, real-time controller, automatic control system, fuzzy control system, optimal solution search method

Introduction

Coal is an important global source of energy, providing 36% of the world's electricity in 2019. It is also essential for the production of cement and steel, with two-thirds of all production used in the electricity sector and the rest in metallurgy, cement production and other sectors. China dominates

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production and consumption, producing 3,550 million tons, or 45% of global production in 2018, and consuming 49% of the global volume [1]. Coal consumption is predominantly domestic, with 82% of the fuel used in the country of origin, in stark contrast to oil (42%) and gas (68%), due to coal's lower energy density and higher transportation costs. Coal with low energy density, below 20 GJ/t, is mostly used near the place of its extraction [2, 3].

However, the use of coal as a fuel for power plants poses certain challenges, including the deposition of slag and ash in boilers, which has been a problem for fifty years. Advances in analytical methods and combustion testing over the past twenty years have improved the understanding and management of ash deposition, and some management techniques have been developed for power plant operators. These documents provide solutions for pulverized coal and cyclone boilers by providing diagnostic methods to identify problems, determine causes, implement corrective actions, and monitor results [4, 5].

Coal-fired boilers also suffer from erosion, which threatens the integrity of pipes and equipment, which can lead to power plant shutdowns. The process of diagnosing such damage is thorough, often relying on interpolated measurements during maintenance due to financial constraints, and replacement occurs when wall thinning is critical. Identification of erosion-prone areas is crucial [6, 7].

In Ukraine, the problems of energy infrastructure are exacerbated by targeted attacks by the aggressor country, which threatens to cause unpredictable power outages that are critical for the country. The war complicates fuel supplies and requires further research into fuel quality and its impact on thermal power plants. Immediate solutions and strategies are needed to restore and preserve energy facilities, and computer technology plays a key role in modelling and solving problems.

Analysis of recent publications and problem statement

The article [7] summarizes that coal quality has a significant impact on the productivity and efficiency of a power plant, as changes in coal quality affect the calorific value, which causes economic and environmental problems. Accurate sampling, which provides equal probability for all coal particles and a sufficient sample size, is essential for quality analysis.

It is also described in [7, 8] that quality control affects numerous operational aspects, including emissions, heat, and costs due to equipment breakdowns, and requires detailed research.

New advances in analytics and modelling are helping to address the problem of ash deposition in boilers and develop mitigation strategies, as well as find applications for ash utilization as described in [4], [9, 10]. Diagnostics of boilers, especially for problems such as wall thinning, is crucial, even though it is labour intensive. New tools described in [11], including EMAT, offer the potential to assess corrosion without descaling.

Erosion in coal-fired boilers can now be predicted and repaired using tools such as Ansys. Fluent [12, 13], which emphasizes the need for improved diagnostic and prevention strategies to ensure the longevity of power plants.

References [14, 15] discuss advanced coal preparation systems (ACPS) for pre-combustion treatment, focusing on grinding, beneficiation, and minimizing environmental impact. Ultra-clean coal (UC) and ashless coal (AC) are considered, which play a role in reducing the ash content. In [16, 17], automated coal quality improvement systems are described to reduce costs and environmental damage, with machine learning (ML) and artificial intelligence (AI) applied to coal flotation processes.

In [18], chemical methods of coal enrichment and the effectiveness of organic solvents at high temperatures to reduce ash content are investigated, although economic estimates are not available, which indicates areas for future research.

The coal quality prediction model from [19, 20] based on genetic algorithms demonstrates improved accuracy, indicating the potential for integrating sensor networks and genetic algorithms in coal preparation for better predictability and environmental efficiency.

Research [9] analyses model-based control and management in coal-fired power plants with a focus on in-combustion sampling and diagnostics and emphasizes the importance of ASTM D7430 recommendations for designing and maintaining samplers to ensure objective results. Predictive maintenance using artificial neural networks is also discussed in [21, 22] to improve boiler efficiency.

Key indicators of coal quality include carbon, ash, and moisture content, as well as changes in the calculation of the water-fuel mixture to improve thermal efficiency [8]. Measurement of coal ash content complies with ASTM D-3174 standards [22].

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Particular attention in [10, 23, 5] is paid to the diagnosis of boiler tubes due to erosion-related failures. Systems for measuring coal dust parameters using the Lambert-Beer law and active thermography for boiler diagnostics are notable advances that affect maintenance strategies.

Article [22] discusses the deterioration of TPP infrastructure, drawing attention to the lack of adaptability of methods in emergency conditions, which can lead to fuel shortages and equipment damage. The combustion of high-ash fuel accelerates the erosion of heat exchanger tubes, and impurities cause permanent damage.

Article [24] raises the issue that existing methods of coal quality control are inefficient, leading to logistical delays and cost overruns due to non-adaptive sampling. It is also discussed in [18, 19] that the presented mathematical models cannot accurately predict operational factors such as fuel consumption and maintenance schedule, and the existing empirical methods for determining coal enrichment factors are unreliable.

The literature review shows a discrepancy between the expected service life and the actual thickness of boiler heat exchanger tubes at TPPs. This discrepancy arises due to the difference in the content of mineral impurities in coal at shipment and during combustion. This problem can be solved by integrating two independent channels for monitoring the heat exchange surfaces of steam boiler tubes into the CICS – one to check the composition of coal and the other to detect refractory compounds (abrasive) in flue gases after coal combustion.

The purpose of the article

The purpose of the article is to improve methods and models for the thermal power plant steam generator tube wear control system by controlling coal quality. The system should dynamically regulate the coal supply depending on its quality, avoiding the use of low-quality fuel and ensuring efficient operation of the plant. To achieve this goal, the following tasks need to be solved:

1. To present a structural simulation model for assessing the impact of coal quality on pipe wear, including mathematical models for minimizing costs and controlling fuel supply.

2. To describe the method of monitoring the condition of pipes, which involves a multicultural approach to logistics, systematic control of fuel quality and an algorithm for managing the coal combustion process.

3. Implement a pipe surface wear control system using fuzzy logic and the Cochran formula to regulate coal flow and control coal quality.

1. Model of the influence of coal quality on the wear of heat exchange tubes of a TPP steam boiler

A comprehensive model (1) of the influence of coal quality on the wear of heat exchange tubes at TPPs is proposed. It provides a mathematical basis for calculating the financial consequences of premature pipe wear due to abrasive impurities in coal, thereby helping to minimize the associated costs. This includes a model for determining hard refractory mineral impurities in coal, which is critical for assessing the quality of the fuel after combustion, as well as a system for ensuring coal quality using algebraic equations. The model also outlines a structural approach to fuel supply logistics management that takes into account potential consumption volumes and reserve losses arising from inconsistent suppliers, with the effect of pipe wear [25]:

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

where: W_{enrich} (Ad, V_{purch}) – is a function that describes the costs associated with the fuel enrichment process, depending on the solid mineral impurities content 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 content of solid mineral impurities in coal;

C_{TPP} $(Ad, \mathrm{T}_{\mathrm{equip}})$ – is a function that describes the costs of TPP related to environmental pollution, repair and replacement of equipment due to the use of highly abrasive fuel, depending on the time of operation before an urgent shutdown for repairs;

T_{equip} (Ad, V_{purch}) – function of calculating the time of current operation before repair.

Function (2) uses an algebraic formula to calculate the costs of a thermal power plant based on variables such as fuel ash content, purchase price, fuel enrichment cost, logistics, environmental impact, and equipment wear and tear:

$$Z = W_{\text{enrich}} + L_{\log} + C_{\text{TPP}} . \tag{2}$$

Assumptions underlying the model include on-site fuel enrichment, equivalence of ash and abrasive content (also referred to as refractory compounds or solid mineral impurities), 87.6% recovery rate at enrichment, and 95% carbon recovery rate at enrichment, with a range of fuel ash content of 0...40%.

The annual costs of TPPs, including repair costs due to abrasive wear from ash, are as follows:

$$C_{\text{TPP}} = \frac{U^{\text{eq.rep.}} + U^{\text{ash collectors rep.}} + U^{\text{ash removal.}} + U^{\text{ash collector rep.}} + U^{\text{storage}}}{365},$$

pecific component costs are calculated using the formula:

$$U^{\text{eq.rep.}} = \frac{U^{\text{F}} + U^{\text{WEC}} + U^{\text{SH}} + U^{\text{CT}}}{Y}.$$

Abrasive wear of the pipeline is taken into account in the model by means of:

$$\delta_{\text{spec.h}} = \frac{5.55 \cdot 10^{-7} \cdot C_{\text{P}} \cdot U_{\text{m}}^{2} \cdot k_{\text{SiO}_2}}{D^2 \cdot m^{0.4} \cdot k_{\text{res}}},$$

efficient for the SiO_2 content is calculated as $k_{\text{SiO}_2} = \frac{n_{\text{SiO}_2}}{94\%}$, where n_{SiO2} – is the percentage of quartz.

The yield of useful components in the beneficiation process is:

$$\varepsilon_{\text{coal}} = \frac{M_{\text{conc}} \cdot I_{\text{enrich}}}{M_{\text{carbone}}},$$

the cost of enrichment according to [26] is presented as follows:

$$W_{\text{enrich}} = 24 \cdot \left(\sum_{n=0}^{r} \frac{G_{\text{m}}}{(I_{\text{conc}})^n \cdot M_{\text{pos}}} \right) \cdot t_{\text{el}} .$$

Table 1 illustrates the relationship between ash content and fuel purchases, which is the basis for developing fuel supply strategies for TPPs.

Table 1

Varying the volume of fuel purchases depending on Ad

Ad	d_{MFU}	Ad_{MF}	k_{MFU}	G_{MFU}	Q_{MFU}	G_M	s	P_{MFU}
15	87.60	7.80	1	3558.60	2160	4637.36	3	3749.76
20	87.60	13.24	1	3558.60	2160	4637.36	3	3749.76
25	76.74	11.79	2	3117.33	4320	5293.79	6	7499.52
30	67.22	10.72	3	2730.70	7920	6043.34	11	13749.12
35	58.89	10.09	4	2392.17	7200	6898.57	10	12499.20
40	51.58	10.00	5	2095.54	8640	7875.07	12	14999.04
45	45.19	10.53	6	1835.69	10080	8989.81	14	17498.88
50	39.58	11.79	7	1608.07	7920	10262.34	11	13749.12
55	34.68	13.91	8	1408.67	12240	11715.00	17	21248.64
60	26.61	10.00	10	1080.98	13680	15266.31	19	23748.48
65	20.42	7.38	12	829.52	15120	19894.17	21	26248.32
70	17.89	13.91	13	726.66	15840	22710.25	22	27498.24
75	12.02	8.49	16	488.47	18000	33783.88	25	31248.00
80	9.23	13.90	18	374.84	19440	44025.20	27	33747.84

Ad – ash content, %; d_{MFU} – is a fraction of the initial fuel mass after fuel enrichment, %; Ad_{MFU} – is ash content after the enrichment stage, %; k_{MFU} – is the number of enrichment iterations; G_{MFU} – is the final volume of fuel after enrichment, ton; Q_{MFU} – is the amount of energy consumed for fuel enrichment, kW·h; G_M – is the initial volume of fuel before enrichment, tons; K_{MFU} – is the number of MFU-25 machines for non-stop operation; P_{MFU} – is the cost of consumed electricity, UAH

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In addition, the logistics costs of TPPs are considered, and the objective function (3) is introduced, which takes into account the ash content of coal and its impact on fuel consumption. The adjusted formula for the daily fuel demand, taking into account the ash content, is as follows (4):

$$Z(W, L, C) \to \min, \tag{3}$$

$$G_{\text{M}}^{*} = \frac{N}{\eta_{\text{TPP}} \cdot Q_{\text{н}}^{\text{р}} \cdot (1 - Ad)}. \tag{4}$$

A purchasing function is proposed for different values of ash content and beneficiation degree, and the logistics costs L_{log} include the cost of fuel per ton, transportation tariffs, and distance to unloading points:

$$L_{\log} = V_{\text{purch}} \cdot (x + l \cdot S),$$

where *x* is the cost of a ton of fuel, *l* is the transportation rate, and *S* is the distance.

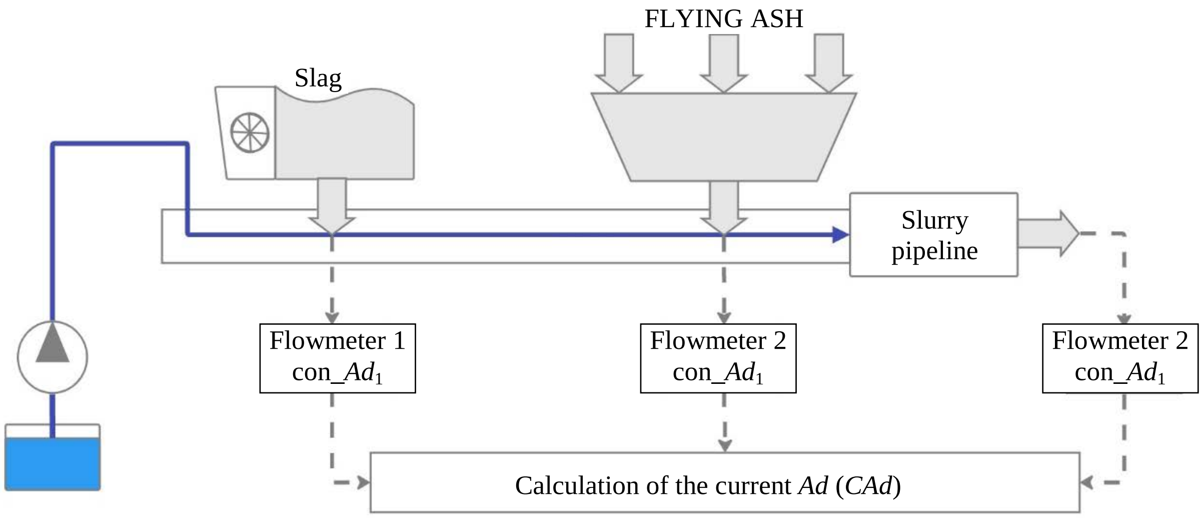

Fig. 1. Monitoring channel of the actual indicator Ad

To measure the actual *Ad*, we propose a measurement channel (Fig. 1) given in [27].

For automated control systems of TPPs, the principle of determining ash content without laboratory tests due to the changing quality of fuel is proposed, highlighting the advantage of the approach to assessing the mass of ash in collectors, since it directly relates solid mineral impurities to ash content. This is more practical for the operational management of TPPs.

2. Method of controlling the surface condition of TPP steam boiler tubes by disturbing the abrasiveness of coal

A multilevel approach to maintaining a satisfactory thickness of heat exchange tubes of steam boilers of thermal power plants aimed at combating the problems associated with abrasive impurities in coal is presented. This strategy integrates:

– Coal supply management: Outlines the logistics plan for coal supply, including supplier selection, transportation and risk management.

– Quality control: Uses the Cochran formula to ensure combustion quality, initiate inspections and manage coal inventory.

– Coal preparation: Offers recommendations for coal preparation to optimize combustion at the power plant, including an algorithm for controlling coal feeding, combustion and exhaust.

– Impurities monitoring: Implements a system for monitoring mineral impurities in flue gases, indicating changes in coal quality.

– A fuzzy logic controller: A regulatory mechanism that directs the flow of coal based on ash content, sampling frequency, and coal batch composition.

For optimal coal logistics, a twelve-step method is introduced, starting with demand estimation using the $V_{purch}(Ad)$ function and ending with process analysis and improvement, as described in [25]. The choice of supplier is crucial based on the assessment of cost, quality, reliability, and emphasizes logistics planning, including with reference to the data of Ukrzaliznytsia for rail transportation [28, 29, 30].

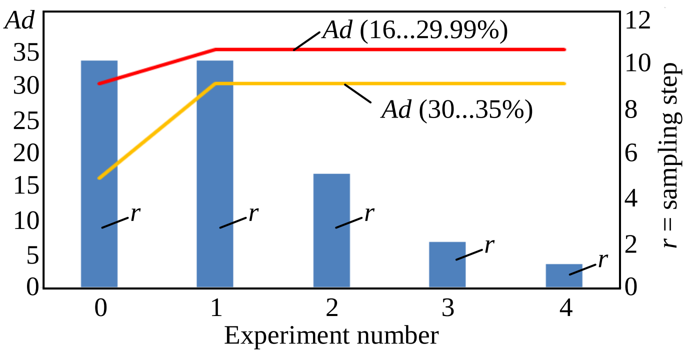

Fig. 2. Sampling recommendations for the content of refractory compounds for unsatisfactory quality

The coal quality control algorithm involves accurate sampling according to the Cochran formula (5), adjusting procedures depending on the quality, and thorough testing to classify coal. The results of quality control influence inventory management and unloading decisions, as detailed in Figure 2 and Table 2.

Table 2

Setting control influences to the relevant coal classes

Ad	fuel class	min, years	max, years	controlling influence
0...5%	Ideal	–	17.75	Transfer to the reserve warehouse
5...9%	Good	17.69	9.43	Use for incineration
9...16%	Normal	9.42	4.89	Partially enrichment or mix with reserve
16...30%	Unsatisfied	4.89	2.17	Enrichment, or enrichment and mix with reserve
30+%	Bad	2.17	–	Mix with the reserve, or use only the reserve

$$Sl_{Wg}=\begin{cases} n_r = n_r(Ng, X); \\ X = X(p); \\ \mathrm{FPC} = \mathrm{FPC}(Ng, X), \end{cases} \tag{5}$$

where n_r – is the sample size;

Ng – 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; specific load of a railroad car;

X – sample size (calculated for FPC);

p – is the expected probability of leakage of low-quality fuel;

FPC – is the limited population correction.

Since the preparation for combustion begins with screening and grinding of coal, it is necessary to consider potential beneficiation, namely wet flotation for low-quality fuel according to mathematical models (1) and (5), and as shown in Fig. 3.

A real-time fuzzy controller was built to control the coal flow and take samples for quality control. Coal is classified into five qualities, each of which has certain control actions (Table 2). The controller ensures the distribution of coal for combustion, reserve replenishment or enrichment, depending on the need, with adjustments for the current fuel quality.

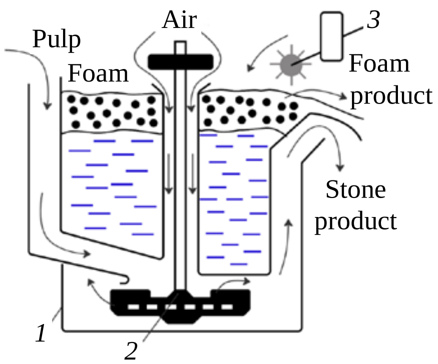

Fig. 3. Schematic diagram of the flotation process: *1* – casing; *2* – mixing and aeration unit; *3* – foam separator

3. Model-oriented CICS wear of the surface of heat exchange tubes of a steam boiler in TPP

A CICS developed in MATLAB® and Simulink® (LICENSING 110721904 – MathWorks Trial – 22 Oct 2022) is presented, designed to monitor and control pipe wear by distributing coal flow and quality control in order to improve the economic efficiency and reliability of thermal power plants (Fig. 4).

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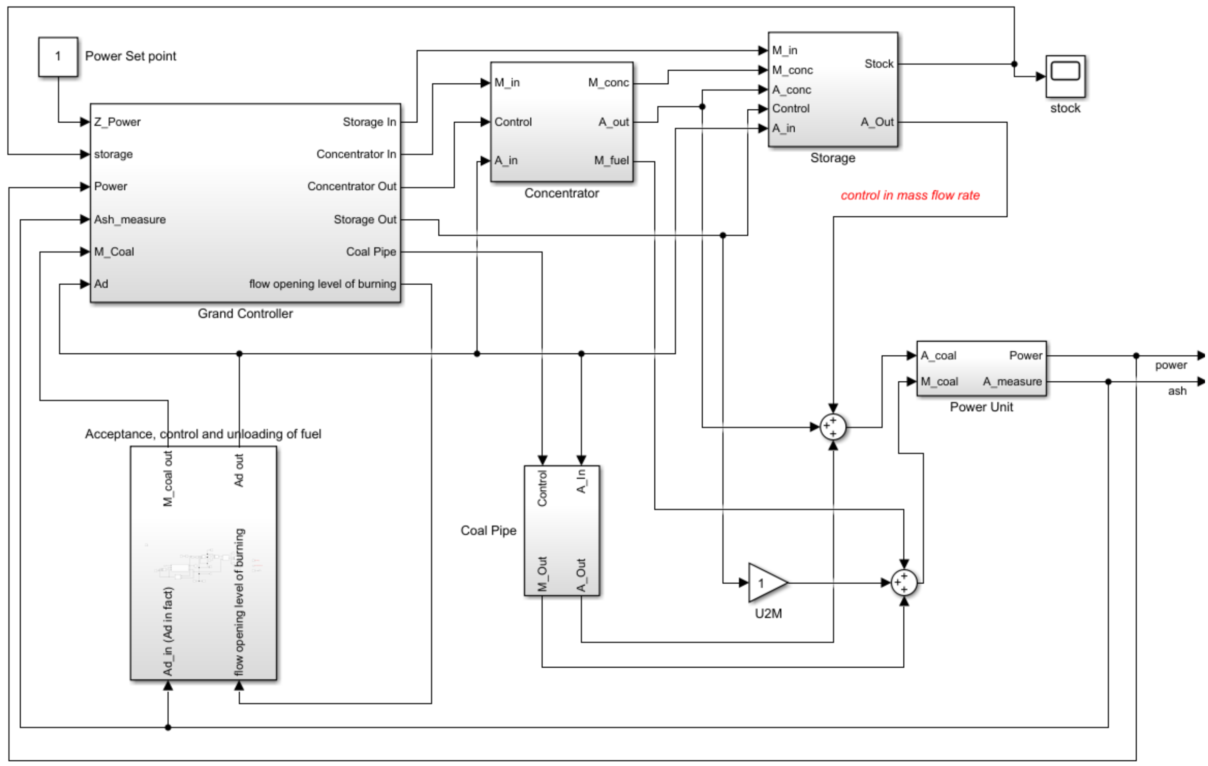

Fig. 4. Simulation system of TPP operation

The system uses fuzzy logic to control wear and tear through coal quality management, based on a study covering nine Ukrainian coal suppliers, one sea delivery route, and includes the Cochran formula to ensure the quality of the coal shipped.

The economic analysis also includes imports of coal from South Africa through the Pivdennyi port, despite its lower quality, as it is more cost-effective due to the beneficiation processes. The three TPPs listed in Table 3 were considered, and the annual coal consumption was estimated, including supplies from the Donetsk coal basin. Mechanical flotation modeling shows that enriched coal, even taking into account costs and carbon losses, optimizes long-term equipment wear and pays for itself [30, 31]. The coal distribution plan takes into account the ash content and quality of coal from various suppliers of the Donetsk coal basin, in addition to the aforementioned imported coal from South Africa (Table 4).

Table 3

Coal needs of TPPs

TPP	Installed electric capacity, MW	Coal consumption, kg/s	Consumption million tons/year
A_1	3600	290.32	9.16
A_2	3600	290.32	9.16
A_3	2400	193.55	6.10

Table 4

Transportation task

			useful volume	real volume	
348.45	124.77	68.64	1.438356		B_1
1652.383592	1631.363195	365.4681826	4.062329	5.803326811	B_2
757.6973391	1096.359289	1001.767503	4.062329	5.80332681	B^*
182.78	54.42	663.97	2.734247		B_3
277.42	95.24	960.39	3.880822		B_4
507.17	179.43	1 672.46	6.981644		B_5
169.99	17.71	23.30	0.689041		B_6
168.65	53.51	607.45	2.346575		B_7
195.79	219.61	428.72	2.465753		B_8
1 721.48	1 603.28	8 451.18	38.23973		B_9
25.08705259	25.08705259	16.72470172	***Z***		
A_1	A_2	A_3	$\Sigma A_n = \Sigma B_m = 66.9$		

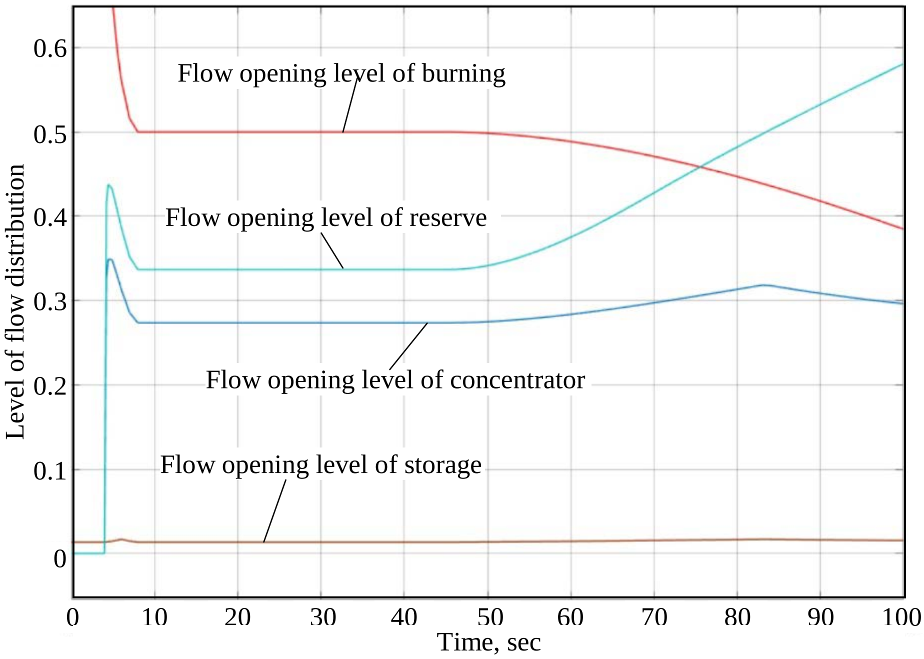

Fig. 5. Dependence of the coal flow distribution between the control influences and the time of the second experiment

The main component of the system in Fig. 4 is the "Grand Controller" block, which regulates the coal flow based on coal classes and control influences from Table 2. Defuzzification processes and rules provide adaptive inventory management and coal flow distribution. The simulations demonstrate the controller's ability to effectively manage the fuel flow in response to different ash contents (Figures 5, 6, 7).

The results are shown in Figure 5 as follows:

– At the initial *Ad*=14% (system operating time t_0=0 s), almost the entire fuel flow is directed to combustion.

– At the system operation time t_1=50 s, *Ad* changes to 24%. As a result, the following distribution of the fuel flow will be the controlling influence – half of the steam coal is sent for combustion, mixing with the reserve fuel, and the rest is sent for enrichment.

– At the end of the experiment (t_2=100), at *Ad*=35%, the largest share of the fuel burned will be thermal coal from the reserve. At the same time, coal from the supplier will be partially burned and partially sent for enrichment.

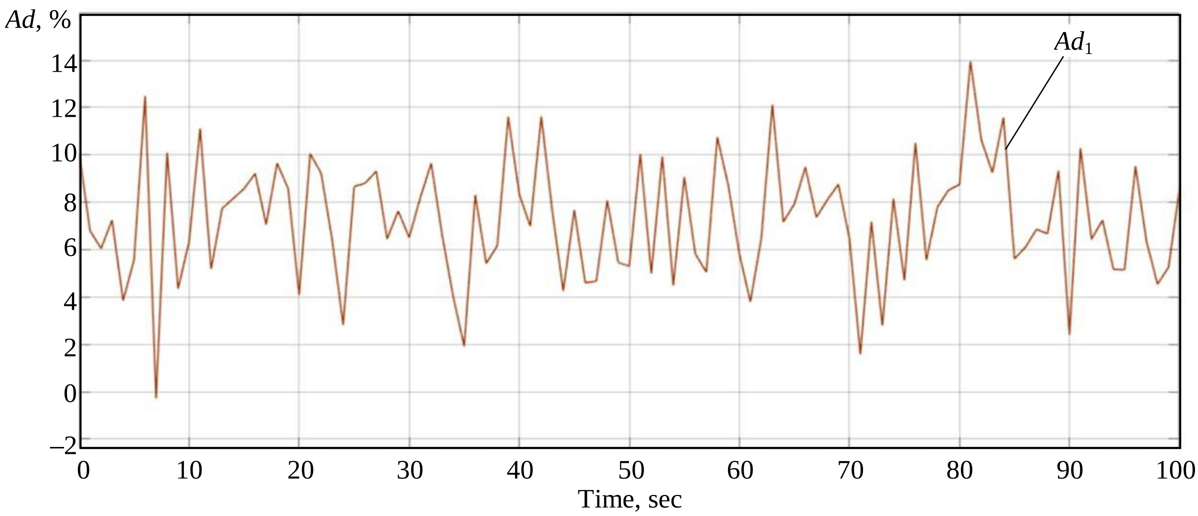

Fig. 6. Random change of *Ad* in the range of 0...30%

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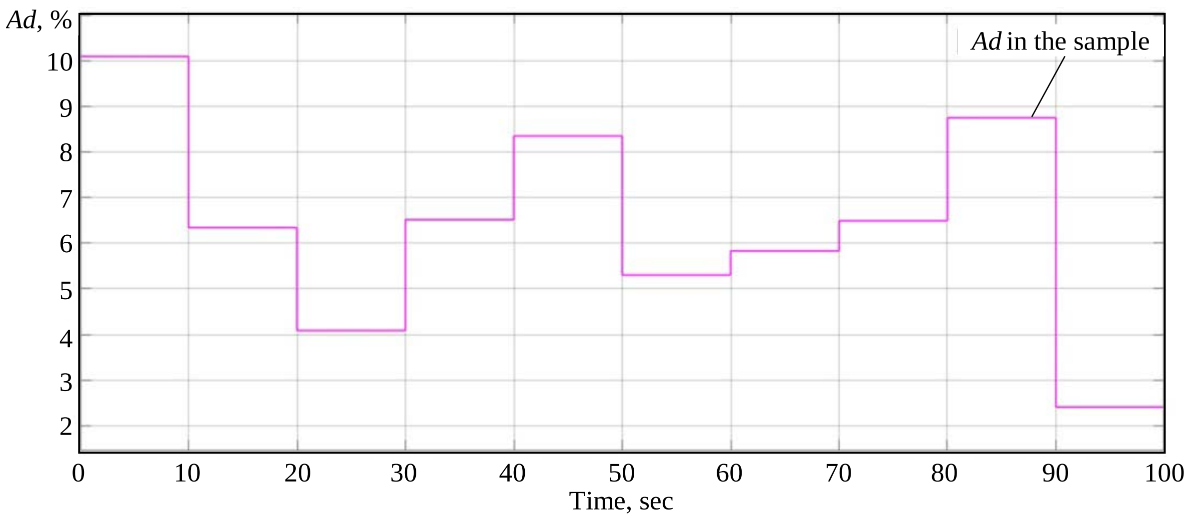

Fig. 7. *Ad* at the time of fuel quality sampling for Fig. 6

To validate the CICS as a whole, an *A*/*B* testing experiment is described to evaluate the impact of the coal feed control system on the wear of the tubes at TPP. The experiment compares scenarios with different average ash content (*Ad*_avg) from coal suppliers and monitors the thickness (*H*_tube, mm) and service life (*T*_left, days) of the heat exchange tubes (Table 5). The following conditions are assumed: TPP receives coal with a satisfactory *Ad*=10% from three suppliers during the year. The initial thickness of the tubes is 10 mm, and they need to be replaced when they reach a thickness of 2 mm. The perturbation is as follows: supplier B_2 provides 20% lower quality coal from day 90, and supplier B_3 provides 30% from day 180.

Table 5

A/*B* Test

A (without CICS)				*B* (Using CICS)			
Day	*Ad*_avg, %	*H*_tube, мм	*T*_left, days	Day	*Ad*_avg, %	*H*_tube, мм	*T*_left, days
0	–	10	–	0	–	10	–
1	10	9.997	3059.9	1	10	9.997	3059.9
2	10	9.995	3058.9	2	10	9.995	3058.9
3	10	9.992	3057.9	3	10	9.992	3057.9
…	…	…	…	…	…	…	…
89	10	9.767	2971.9	89	10	9.767	2971.9
90	13.33	9.764	2209.8	90	13.33	9.764	2209.8
91	13.33	9.76	2208.8	91	8.33	9.762	3629.9
…	…	…	…	…	…	…	…
103	13.33	9.717	2196.8	103	8.33	9.736	3617.9
104	13.33	9.713	2195.8	104	10	9.733	2957.8
…	…	…	…	…	…	…	…
179	13.33	9.442	2120.8	179	10	9.537	2882.8
180	20	9.436	1303.1	180	16.67	9.532	1600.2
181	20	9.43	1302.1	181	8.33	9.53	3521.8
…	…	…	…	…	…	…	…
193	20	9.36	1290.1	193	8.33	9.505	3509.8
194	20	9.353	1289.1	194	10	9.502	2866.9
…	…	…	…	…	…	…	…
363	20	8.36	1120.1	363	10	9.06	2697.9
364	20	8.353	1119.1	364	10	9.058	2696.9
365	20	8.347	1118.1	365	10	9.055	2695.9

Fig. 6 shows the dynamics of the change in the random value of *Ad* from 0 to 30% over 100 time units. In this scenario, the control device continuously adjusts the sampling depending on the detected refractory compound content (Fig. 7). For example, at 0 s, when *Ad* is 19%, this resulted in a decrease in the sampling step r=1 and forced the system to switch to signal 1092 due to a 4 s delay associated with sample analysis. Another illustrative example is presented at 10 s of the simulation, when the actual content of refractory compounds is 12% (satisfactory quality), the sampling step at this time interval is every 10th car, taking into account the transport delay, signal 840 returns for 52 s. Also, the system operation is clearly demonstrated from 78 to 84.5 s, when the actual *Ad* becomes 15.5%, which leads to a sampling step of 79 s – every 5th car. After the coal re-enters the furnace, between 81 s and 82 s, the sampling step is set to every 2nd car, and between 82 s and 83 s, every first car. At the 83rd second, the actual value of *Ad*=17.5%, the sampling also showed *Ad*=17.5%, and the recommended number of cars per day of intake is 1092.

Without the use of CICS, the average *Ad* rate from the three suppliers increases to 13.3% from day 90, and to 20% from day 180. With the use of CICS, a high content of solid mineral impurities is detected on the 90th day and on the 180th day. Accordingly, TPP refuses to use fuel from unscrupulous suppliers. The pipe thickness at the end of the first day is 9.997 mm. Given *Ad*=10%, if not for the disturbance, the pipes are expected to last 3060 days (about 8 years). However, these results change due to the change in *Ad*. Without CICS, the pipe thickness at the end of the year will be 8.35 mm. This means that the pipes will be able to serve for about 3 years before repair. With CICS, the end-of-year pipe thickness is 9.06 mm, and the pipes can last approximately 7.5 years before needing to be repaired. The results show that the system extends the life of the pipes by strategically managing coal quality, reducing wear and tear, and reducing the frequency of maintenance.

Conclusions

The paper presents a CICS for steam boiler tube wear at TPP by improving wear control through real-time coal quality management and real-time coal flow control. CICS adjusts the coal flow and quality checks at different Ad values in coal from different suppliers, optimizing costs and extending the overhaul life.

A mathematical model (1) and a target function (3) were developed to predict the total costs associated with the use of high-ash coal, including beneficiation, logistics, environmental impact, and equipment wear and tear. The model is aimed at optimizing fuel consumption by directly taking into account the ash content of coal and the use of flotation equipment for coal beneficiation.

Given the variability of fuel quality and the limited resources of TPPs to conduct ongoing laboratory research, the paper emphasizes the importance of accurate ash content analysis using flow meters to measure *Ad*. A mathematical model was also developed to control the quality of coal in railroad transportation, which takes into account the variability of supplies to ensure efficient power generation.

To control the properties of fuel, the article describes methods that control the quality of coal by constantly changing the sampling step according to the Cochran principle, ensuring combustion efficiency and extending the service life of heat exchange tubes of the TPP steam boiler.

The logistics of coal supply for three Ukrainian TPPs were analysed, annual coal supplies were balanced, and imports from South Africa were taken into account. The beneficiation process, which significantly reduces ash content, proved to be cost-effective for ten years.

A control device based on fuzzy logic was created to manage the wear of the TPP heat exchange surface, taking into account ash content and stock levels, which allows optimizing the distribution of coal flows. In addition, a control device was implemented to manage the quality of coal from different suppliers, allowing for real-time quality monitoring and supplier adjustments.

A CICS was also developed to allocate coal flow in response to changes in coal quality, maintain pipe thickness and significantly increase pipe life before repair, improving TPP efficiency and saving money.

Finally, a computational experiment was conducted that confirmed the effectiveness of CICS by increasing the overhaul life from 3 to 7.5 years, taking into account the disturbance.

In future, it would be preferable to consider the possibility of introducing machine learning for coal quality control models in order to reduce the error and increase the stability of the models.

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