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Automated solid fuel quality control and monitoring system

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ABSTRACT

The article describes the development of a computer-integrated coal quality management system that allows to increase the service life of heating surfaces in boilers of coal-fired power plants. The need for such a system arises due to erosion caused by abrasive impurities in coal, which leads to deterioration of the boiler infrastructure. Existing methods are mostly manual, time-consuming and error-prone. The aim of the work was to increase the service life of the surface wear resistance of heat exchange tubes of a steam generator of a thermal coal-fired power plant by synthesizing and analyzing a computer-integrated coal quality management system by distributing coal flows between different coal supply sources, unloading conditions and coal quality inspection from suppliers to minimize costs. To achieve this goal, a mathematical model was developed that describes the boiler unit in terms of ash flows in the form of a system of equations. A computer-integrated coal quality control system has been developed that allows to increase the service life of heating surfaces of power boilers by distributing coal flows between coal supply sources and conditions of unloading and checking the quality of coal from suppliers to minimize costs. A computational experiment was conducted to test the operation of the computer-integrated control system and confirm its effectiveness. The results proved the value of the developed computer-integrated control system for increasing the service life of the boiler unit's heating surfaces by timely responding to changes in the quality of coal from different suppliers. It was found that with a computer-integrated control system, the service life of the pipes could be more than doubled (from 3.06 years to 7.39 years). Overall, the introduction of a computer-integrated control system is a transformational solution for managing the distribution of costs between fuel and equipment repair costs. The integrated system, together with the use of mathematical modeling and computational experiments, offers a comprehensive approach to monitoring, predicting, and controlling the factors that affect the durability of heat exchanger tubes. This research makes a significant contribution to the power industry, potentially transforming maintenance and life extension practices for critical infrastructure in thermal power plants. Further research is needed to refine the system and explore its wider applicability in different operational scenarios.

Keywords: Thermal power plants; coal quality; supplier selection; computer-integrated control systems; quality control; automatic control system; simulation modelling, mathematical modelling

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INTRODUCTION

The coal industry is an important component of the global energy sector, with about 3.5 billion tons of hard coal produced annually. The majority of this production, over 85 %, meets domestic demand [1, 4], which demonstrates the continued dependence of many economies on coal. Despite growing environmental concerns and policies aimed at reducing solid fuel consumption, coal remains a critical component of energy production systems in many countries. This is especially true in developing countries, where coal is a relatively cheap and accessible energy resource.

Coal quality analysis is a critical aspect of coal-fired power plant operations, as it significantly influences decisions on cleaning methods, power generation, and grinding operations. An important part of this process is coal sampling, which, if done correctly, allows for accurate quality control.

A common problem with coal-fired boilers is the erosion of the surfaces of pipes and equipment in coal-fired power plants, which can lead to system failure and, as a result, shutdown [5, 6], [7, 8]. There is a limited number of studies of dust erosion of dust ducts that supply the dust-air mixture to the burners. However, the deterioration of the dust duct material can lead to a mill shutdown due to erosion and, possibly, to a power plant unit shutdown. The processes of diagnosing damage to furnace screens are labour-intensive and are preceded by thorough mechanical cleaning of their surfaces. After cleaning, the surfaces are ground for measurement. To save on costs, the measurements are interpolated during the reconstruction process; only a few pipes are measured and the rest of the data is estimated. Based on the wall thickness distribution, screens are replaced in areas where the wall thinning is less than 2-3 mm. It is very important to identify areas prone to coal dust erosion.

A notable factor contributing to the wear and tear of therma power plant (TPP) infrastructure is the combustion of viscosity fuel. Highly ash fuel, especially if it is contaminated with abrasive impurities, makes a significant contribution 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.

Maintenance and inspection of boilers present significant challenges due to hazardous conditions and large scaffolding. Boiler failure can lead to human casualties, expensive equipment repairs, and increased energy costs.

LITERATURE OVERVIEW

It is described in [9,10], [11] that standard elements of an automated control system (ACS) involve gradually increasing the furnace temperature to 750◦C over several hours and analyzing the amount of various oxides. Some analytical methods include atomic absorption and X-ray fluorescence. The fusibility of coal ash correlates with the difficulty of slagging, clogging and clinking. The mineral content of coal is determined by treating the sample with aqueous hydrofluoric acid at 55-60◦C. This method, however, requires a separate determination of pyrite. The chemical composition of coal ash affects the choice of cleaning methods, coke production technology and grinding operations. During the combustion or removal of ash, trace elements in coal released to the environment are increasingly becoming a subject of interest.

Ash samples require slow combustion to avoid the retention of sulfur as sulfates. The ratio of sulfur to calcium in the coal and the ashing temperature affect the retention of sulfur. Faster combustion can result in sulfur oxides from pyrite forming stable sulfates, which complicates the analysis results. The use of computer integrated control system (CICS) [10] sampling recommended by ASTM D7430 is used to provide mathematical evidence of the correctness of the sampling from the coal stream being sampled.

Particular attention in [11] is paid to the expected service life of boiler tubes, highlighting critical damage mechanisms, progressive failure paths, and appropriate test and measurement procedures. Methods for estimating service life concerning hardness, wall thickness, scale formation, microstructure, and creep are discussed. For example, a method for determining the residual life of a secondary superheater pipe is given as an example.

Papers [12, 13] present a systematic approach to predicting ash deposits in coal-fired boilers using artificial neural networks. The approach has a "grey box" character, breaking the problem into logical parts and eliminating the need for complex data. The model can be used online and is very detailed, taking into account both deposition rates and short-term cleaning phenomena. With a sufficient number of heat transfer measurements, the procedure can predict the heat absorption by the boiler under realistic fouling conditions.

The authors of [14, 15] discuss the growing use of robotics in power plants, noting two significant technological gaps: real-time repair capability and intelligent autonomy through artificial intelligence. An integrated autonomous robotic platform equipped with compact non-destructive evaluation (NDE) sensors for real-time inspection and onboard repair devices for real-time repair is also discussed.

It is noted that no comprehensive approach to measuring fuel abrasive wear and its impact on pipes in real time has been proposed. Similarly, there is no system for controlling the heat transfer surface, which would be based on the rules of interaction with the current coal and take into account changes in real time. The existing control measures rely heavily on predefined coal quality, which indicates the inflexibility of the system. There is no computer-integrated system for monitoring the wear resistance of the surface of the steam generator heat exchange tubes. Also, no tools have been proposed to redistribute the coal flow between enrichment, replenishment, combustion and switching to high-quality reserve fuel based on the current abrasiveness of coal, and no adaptive sampling management has been implemented to minimize TPP operating costs and ensure a certain overhaul period.

THE PURPOSE OF THE ARTICLE

The aim of the research is to synthesise and investigate a computer-integrated control system that allows to increase the service life of heating surfaces of TPP boilers by controlling the distribution of coal flows between coal supply sources, unloading conditions and quality checks of coal from suppliers to minimise costs.

To achieve the goal, it is necessary to:

– develop a mathematical model that describes the boiler unit in terms of ash flows in the form of a system of equations;

– to synthesise a coal quality control system that will increase the service life of heating surfaces of power boilers by distributing coal flows between coal supply sources and unloading conditions and checking the quality of coal from suppliers to minimise costs;

– conduct a computational experiment to verify the operation of the CICS and confirm its effectiveness.

MAIN PART.

1. MATHEMATICAL MODEL OF THE PARAMETRIC SCHEME OF THE BOILER UNIT

To build a mathematical model, we first considered the parametric scheme from [16] and transformed it into Fig. 1 to understand the relationships of information flows at TPPs. These connections were combined in the form of a system of equations (1).

$$\begin{cases} M_{sl} = \mathrm{M}_f \mathrm{a}_1 + \mathrm{M}_{f\_a} a_2 + M_{Ad} a_3 \\ M_{loss} = \mathrm{M}_f b_1 + \mathrm{M}_{f\_a} b_2 + M_{Ad} b_3 \\ V_{res} = \mathrm{M}_f c_1 + \mathrm{M}_{res} \mathrm{c}_2 + \mathrm{M}_{en} c_3 \\ T_{op} = \mathrm{M}_f d_1 + \mathrm{M}_{f_a} d_2 + M_{Ad} d_3 + \mathrm{M}_{res} d_4 + \mathrm{M}_{en} d_5 \\ N = \mathrm{M}_f \mathrm{e}_1 + \mathrm{M}_{res} \mathrm{e}_2 + \mathrm{M}_{en} \mathrm{e}_3 \end{cases}, \quad (1)$$

where $\mathrm{a}_n, \mathrm{b}_n, \mathrm{c}_n, \mathrm{d}_m, \mathrm{e}_n$ are constant coefficients, $n = \overline{1,3}, m = \overline{1,5}$; $\mathrm{M_f}$ – fuel consumption, kg/h; M_{en} is enriched fuel consumption, kg/h; M_{res} is reserve fuel consumption, kg/h; M_{f_a} is ash consumption from ash collectors, kg/h; M_{Ad} is ash content of the fuel, %; M_{sl} is consumption of the total amount of ash and slag slurry, kg/h; T_{op} is the operating time until the heat exchanger tubes are replaced, hours; M_{loss} is carbon losses due to the discrepancy between the declared and actual ash content, which is insufficient, which necessitates enrichment or the use of reserves, kg/h; V_{res} is fuel stock in the reserve warehouse, tons; N is power plant capacity, MW.

The parametric scheme was adapted to focus on three main indicators: current reserve stock level, time to repair and replacement, and current fly ash flow (Fig. 2).

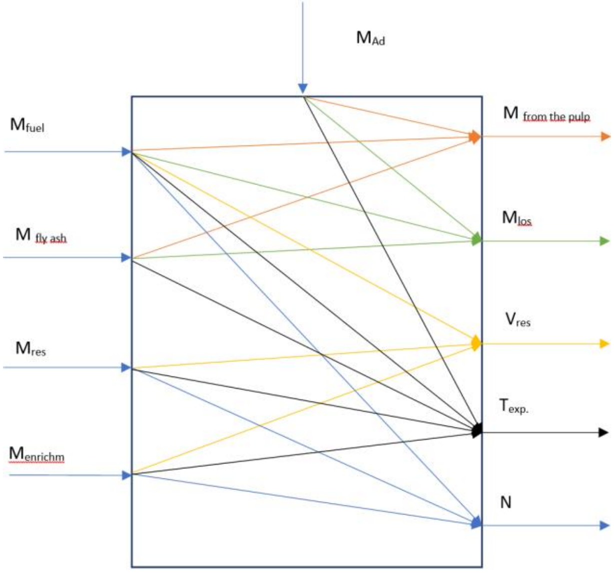

Fig. 1. **Parametric diagram of the boiler unit**

Source: **compiled by the authors**

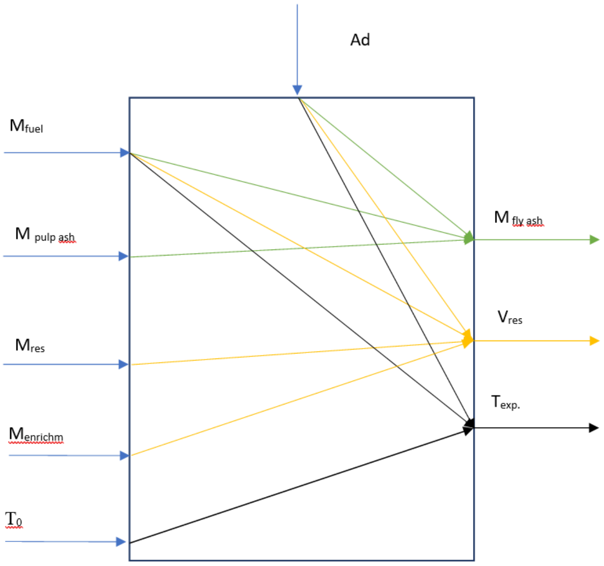

Fig. 2. **Adapted parametric scheme of a thermal power plant boiler unit**

Source: **compiled by the authors**

In accordance with Fig. 3, the system of equations (1) was presented in the following form (2).

$$\begin{cases} M_{f\_a} = M_{sl} - F_{f\_a}(M_f, A_d) \\ V_{res} = V_0 - F_{en}(M_f, A_d, M_{en}) \\ T_{op} = T_0 - F_T(M_f, A^d,) \\ \qquad M_{ash} - M_{sl} = 0 \end{cases}, \qquad (2)$$

where M_{ash} is the total ash consumption.

To understand how a system evolves over time, a static solution is not enough. To build a mathematical model, it is necessary to use differential equations that describe how the quantities in the system change over time (3):

$$\begin{cases} \frac{dM_{A_d}}{d\tau} = (M_{ash} + dM_{ash}) - (M_{sl} + dM_{sl}) \\ \qquad \frac{dM_{A_d}}{d\tau} = dM_{ash} - dM_{sl} \end{cases}. \qquad (3)$$

Thus, the system of differential equations (3) represents the time evolution of the system that was previously described by static algebraic equations (2). By converting the static equations into differential equations, it was possible to track and predict how the system changes over time. In (3), τ is used to denote time and system (3) describes the change. Each equation term in these differential equations describes the rate of change of M_{Ad} over time.

The mathematical model of the TPP boiler unit, represented as a system of equations, defines the relationships between various parameters, including fuel consumption, ash consumption, reserve stocks, and time to repair. The model has been adapted to focus on the evolution of reserve stocks, time to repair, and current ash consumption. The transition from static algebraic equations to differential equations allowed the system to be monitored and predicted over time, providing a valuable tool for strategic planning and optimization at the TPP.

2. WEAR RESISTANCE OF THE SURFACE OF HEAT EXCHANGE TUBES OF A STEAM BOILER OF A THERMAL POWER PLANT

Based on previous studies that indicate the possibility of controlling the wear resistance of pipes through the timely detection of an abrasive impurity in coal and coal quality management, this section sets the task of developing a computer-integrated system for controlling the wear resistance of the surface of heat exchange pipes of boiler units. In [17] and [18], the elements of the ACS were developed using the interactive tool MATLAB®, Simulink® and the system was simulated under various abrasion conditions. The basis of this system is the distribution of the coal flow between the control influences and the conditions of unloading and quality inspection of coal from suppliers, which is aimed at minimizing costs and ensuring the reliability of TPP operation. Such an integrated approach is expected to significantly improve the management of the wear resistance of heat transfer surfaces, opening up new perspectives in the field of efficient coal utilization and ensuring the stability of the power system. It is necessary to combine the elements of the ACS from [19] and [20] into a common CICS.

The CICS is shown in Fig. 3.

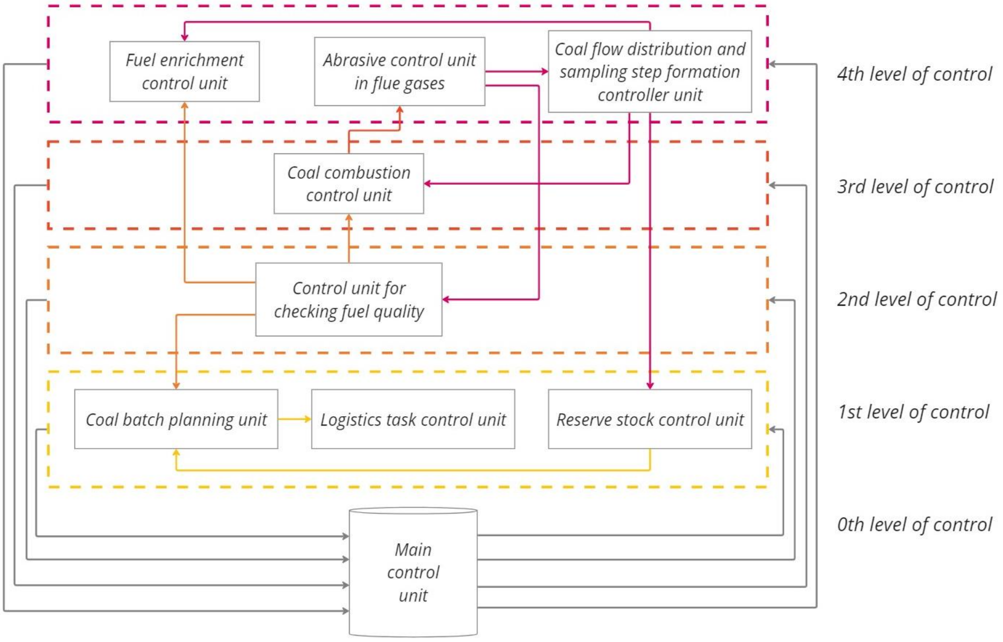

Fig. 3. **Diagram of the wear resistance of the surface of heat exchange pipes of the steam generator of a thermal power plant**

Source: **compiled by the authors**

3. COMPUTATIONAL EXPERIMENT

In order to verify the operation of the CICS on the surface of the heat exchanger tubes of the TPP steam generator, a computational experiment based on the principle of A/B testing (also known as bucket testing or split testing [21, 22], [23, 24]. [25]) was carried out. For the purposes of this computational experiment, the following conditions are assumed: A TPP receives coal batches with a satisfactory abrasiveness index *Ad* = 10 % from three suppliers B_1, B_2, and B_3 during the year. The initial thickness of the pipes is 10 mm, and they need to be replaced when they reach a thickness of 2 mm. Further, it is assumed that supplier B_2 starts supplying lower quality coal of *Ad* = 20 % from day 90 and supplier B_3 supplies coal of *Ad* = 30 % from day 180.

Two scenarios are considered:

A) Without CICS: the suppliers remain unchanged and the abrasive damage to the pipes progresses according to the current abrasiveness index (Table 1).

B) With the developed CICS: controlling the effects of the regulators of the CICS will allow timely management of the wear resistance of the surface of heat exchange tubes of the TPP steam generator (Table 2).

Where *Ad_avg* is the average abrasiveness index for all three suppliers (the change in *Ad_avg* is shown in Fig. 4), *H_tube* is the current pipe thickness (the change in *H_tube* is shown in Fig. 5), *T_left* is the number of days the TPP will operate before repair (the change in *T_left* is shown in Fig 6).

Table 1. **Without computer integrated control system**

Day	*Ad_avg, %*	*H_tube, mm*	*T_left, days*
0	-	10	-
1	10	9.997	3059.85
2	10	9.995	3058.85
3	10	9.992	3057.85
…	…	…	…
89	10	9.767	2971.85
90	13.33	9.764	2209.81
91	13.33	9.760	2208.81
…	…	…	…
103	13.33	9.717	2196.81
104	13.33	9.713	2195.81
…	…	…	…
179	13.33	9.442	2120.81
180	20	9.44	1303.12
181	20	9.43	1302.12
…	…	…	…
193	20	9.36	1290.12
194	20	9.35	1289.12
…	…	…	…
363	20	8.36	1120.12
364	20	8.35	1119.12
365	20	8.35	1118.12

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

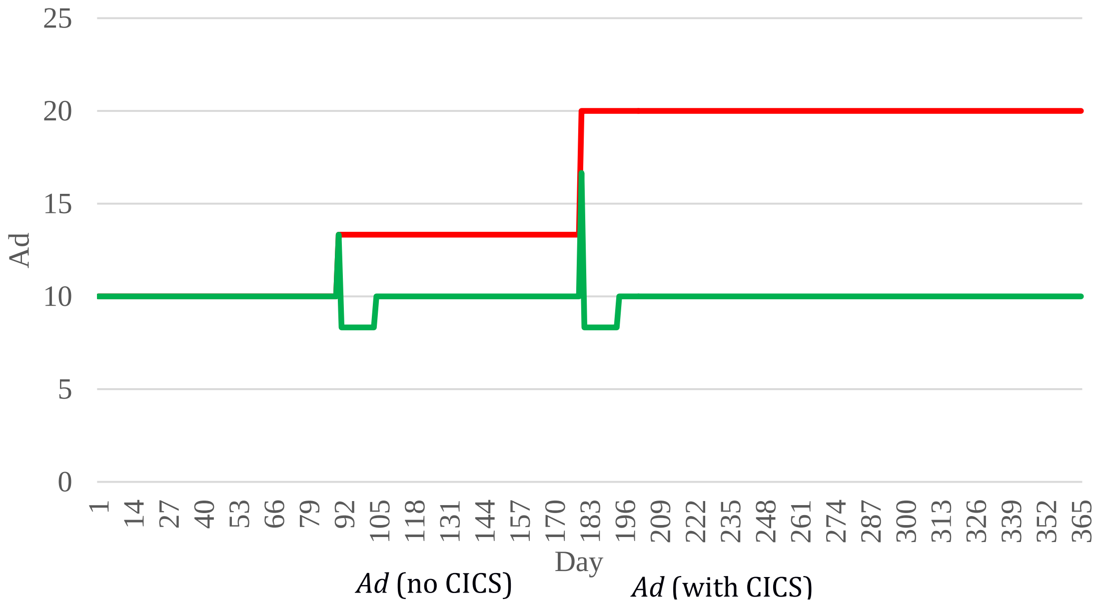

Fig. 4. ***Ad_avg* changes during the year**

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

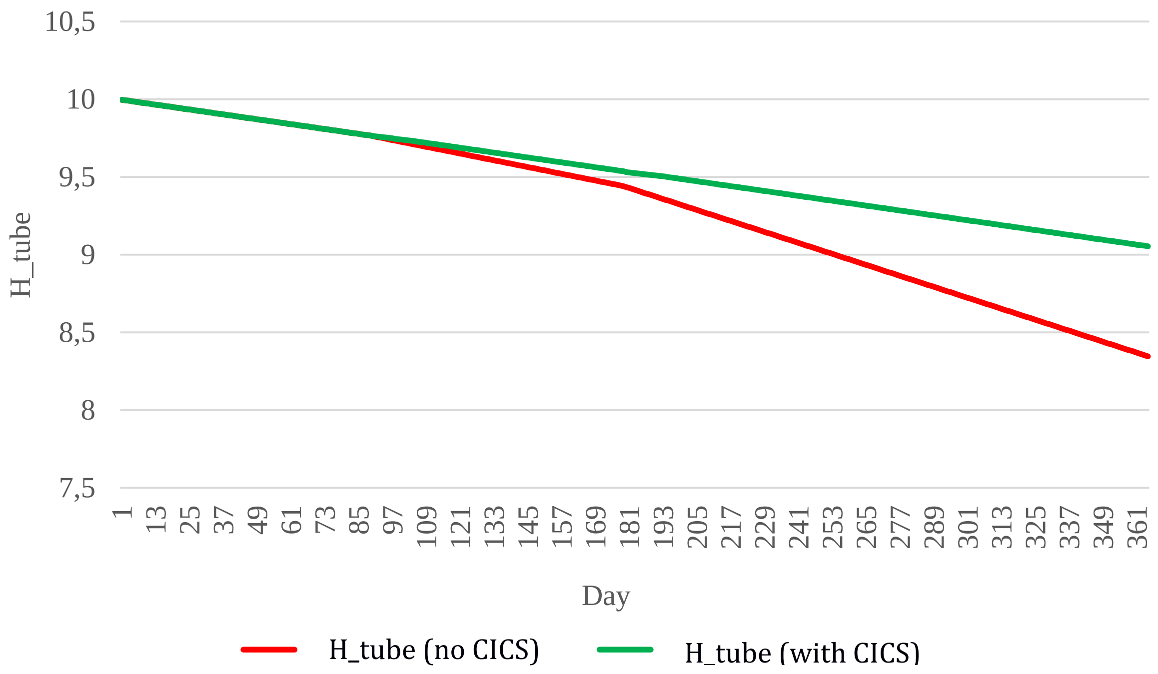

Fig. 5. ***H_tube*** **changes during the year**

Source: **compiled by the authors**

Table 2. **With using developed CICS**

Day	*Ad_avg, %*	*H_tube, mm*	*T_left, days*
0	-	10.00	-
1	10.00	9.997	3059.85
2	10.00	9.995	3058.85
3	10.00	9.992	3057.85
…	…	…	…
89	10.00	9.767	2971.85
90	13.33	9.764	2209.81
91	8.33	9.762	3629.93
…	…	…	…
103	8.33	9.736	3617.93
104	10.00	9.733	2957.83
…	…	…	…
179	10.00	9.537	2882.83
180	16.67	9.532	1600.19
181	8.33	9.53	3521.8
…	…	…	…
193	8.33	9.505	3509.8
194	10.00	9.502	2866.85
…	…	…	…
363	10.00	9.06	2697.85
364	10.00	9.058	2696.85
365	10.00	9.055	2695.85

Source: **compiled by the authors**

Fig. 4 shows that in the first scenario, the average *Ad* rate of the three suppliers increases to 13.33 % from day 90 and to 20 % from day 180, while in the second scenario, the CICS responds to the detection of abrasive on day 90 when the average *Ad* rate of the three suppliers reaches 13.33 %. The TPP refuses coal from B_2 and starts using a reserve stock with a quality index of 5 %. This reduces the average *Ad* to 8.3 % on day 91. On day 104, deliveries from the new B2 begin, restoring the average Ad to 10 %, as set by the terms and conditions. A similar process occurs on day 180 when the average Ad for the three suppliers reaches 16.67 % (due to a 30 % deterioration in quality from B3) – the TPP stops supplying coal from B3, uses the reserve stock and restores the average Ad to 10 % on day 194.

Fig. 5 and Fig. 6 show that the pipe thickness on the first day is 9.997 mm. Given a coal quality of *Ad* = 10 %, the TPP is expected to operate for 3'059.85 days (about 8.38 years) before repair. Under the first scenario, the pipe thickness at the end of the year will be 8.347 mm, which means that, given the dynamics of coal quality changes, the TPP will be able to operate for another 1'118.12 days (approximately 3.06 years) before the need for repairs. Under the second scenario, the pipe thickness at the end of the year would be 9,055 mm, and the TPP would operate for another 2,695.85 days (approximately 7.39 years) before needing to be repaired.

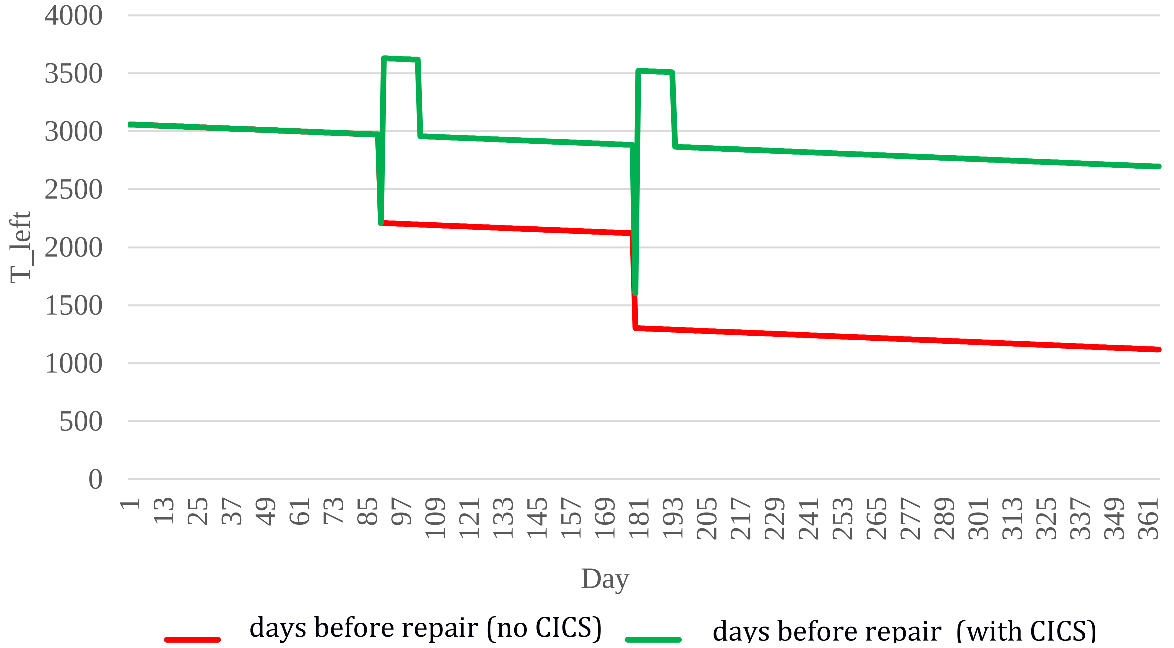

Fig. 6. ***T_left*** **changes during the year**

Source: **compiled by the authors**

These scenarios illustrate the key role of the CICS in maintaining the thickness of the heat exchanger tubes, thereby extending the period before repairs are required and increasing the overall operational efficiency and longevity of the plant.

CONCLUSIONS

This paper presents the development and research of the CICS for the quality of coal combusted in steam boilers of TPPs. The following results were obtained.

1. A mathematical model of a steam boiler unit in terms of ash flows in the form of an equation system is presented. The model is used to analyse the behaviour of three key indicators: the current volume of coal reserves, the time of operation of the pipes before repair, and the current flow of fly ash. The use of differential equations has expanded the possibilities of monitoring and forecasting the development of the system over time, which serves as a powerful tool for strategic planning and optimisation.

2. A coal quality control system for combusted coal has been proposed, the purpose of which is to reduce erosion wear of boiler unit tubes by timely detection of abrasive impurities in coal. The successful development of this CICS opens up new opportunities for improving the operating conditions of heating surfaces and increasing the reliability of TPP operations.

3. A computational experiment was carried out to compare two scenarios, one traditional, without coal quality control, and the other with the use of the CICS, to highlight the impact of the system on the service life of the heat exchange tubes of the TPP boiler unit. The results proved the feasibility of developing a CICS for the efficient operation of boiler equipment by timely responding to changes in coal quality from different suppliers. It was found that with the presence of the CICS, the possibility of operating the pipes can be more than doubled (from 3.06 years to 7.39 years)

Overall, the implementation of the CICS represents a transformational solution for managing wear resistance in TPP operations. The integrated system, together with the use of mathematical modelling and computational experiments, offers a comprehensive approach to monitoring, predicting and controlling the factors affecting the durability of heat exchanger tubes. This research makes a significant contribution to the power industry, potentially transforming maintenance and life extension practices for critical infrastructure in thermal power plants. Further research is needed to improve the system and explore its wider applicability in different operational scenarios.

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Автоматизована система контролю та моніторингу якості твердого палива

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АНОТАЦІЯ

У статті описано розробку комп'ютерно-інтегрованої системи керування якістю вугілля, що дозволяє збільшити термін експлуатації поверхонь нагріву в котлах вугільних електростанцій. Потреба в такій системі виникає через ерозію, спричинену абразивними домішками у вугіллі, що призводить до погіршення стану інфраструктури котла. Існуючі методики є переважно ручними, трудомісткими та схильними до помилок. Мета роботи полягала у підвищення терміну служби зносостійкості поверхні труб теплообміну парогенератору теплової вугільної елекростанції за рахунок синтезу і аналізу комп’ютерно-інтегрованої системи керування якістю вугілля за рахунок розподілу потоків вугілля між різними джерелами постачання вугілля, умовами вивантаження і перевірки якості вугілля від постачальників для мінімізації витрат. Для досягнення мети, було розроблено математичну модель яка описує котлоагрегат з точки зору зольних потоків у вигляді системи рівнянь. Розроблено комп’ютерно-інтегровану систему керування якості вугілля, що дозволяє збільшити термін експлуатації поверхонь нагріву енергетичних котлів, за рахунок розподілу потоків вугілля між джерелами постачання вугілля та умовами вивантаження і перевірки якості вугілля від постачальників для мінімізації витрат. Проведено розрахунковий експеримент, для перевірки роботи комп’ютерно-інтегрованої системи керування і підтвердженню її ефективності. Результати довели цінність розробленої комп’ютерно-інтегрованої системи керування для збільшення терміну експлуатації поверхонь нагріву котлоагрегату шляхом своєчасного реагування на зміни якості вугілля від різних постачальників. Було виявлено що при наявності комп’ютерно-інтегрованої системи керування можливість експлуатації труб можна подовжити більше ніж вдвічі (з 3,06 років до 7,39 років). В цілому, впровадження комп’ютерно-інтегрованої системи керування являє собою трансформаційне рішення при управлінні розподілом витрат між витратами на паливо та витратами на ремонт обладнання. Інтегрована система, разом з використанням математичного моделювання та обчислювальних експериментів, пропонує комплексний підхід до моніторингу, прогнозування та контролю факторів, що впливають на довговічність труб теплообмінників. Це дослідження робить значний внесок енергетичну промисловість, потенційно трансформуючи практики технічного обслуговування та продовження терміну служби критичної інфраструктури теплових електростанцій. Необхідні подальші дослідження для вдосконалення системи та вивчення її ширшого застосування в різних експлуатаційних сценаріях.

Ключові слова: Теплові електростанції; якість вугілля; вибір постачальника; комп’ютерно-інтегровані системи управління; контроль якості; автоматична система управління; імітаційне моделювання, математичне моделювання

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