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Computer-integrated system for controlling the wear resistance of heat exchange tubes of solid fuel boilers with the distribution of coal flows between control influences

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Abstract : *This article presents the development of a computer-integrated control system for optimizing the wear resistance of heat exchange tubes in solid fuel boilers. The proposed model accounts for the quality and abrasiveness of solid fuel, which significantly impacts boiler efficiency and maintenance costs. The system integrates two independent monitoring channels: one assessing the chemical composition of the fuel and the other analyzing the abrasive content in flue gases. By dynamically adjusting fuel distribution, the system minimizes erosion of heat exchange surfaces, prolongs the operational lifespan of boiler components, and reduces downtime. Simulation results confirm the system's effectiveness in enhancing thermal efficiency and operational stability. The proposed approach offers a viable solution for improving the reliability and sustainability of solid fuel energy systems.*

Keywords : *solid fuel steam boiler , quality of solid fuel , computer-integrated control system , wear resistance of heat exchange surfaces , abrasiveness of solid fuel*

Introduction

Coal is the second largest source of primary energy after oil and occupies almost 26% of the world energy market. In addition, coal is of primary importance in the production of electricity, cement and steel. Approximately two-thirds of the world's coal production is spent on electricity production and about 15% is used in the metallurgical industry [1-2].

The total annual world coal production is 7,813 million tons. The main world leaders in coal production are: China, India, the USA, Indonesia and Australia. The top ten largest coal consumers are also headed by China, followed by India, the USA, Germany, Turkey and South Africa. The main feature of this type of fuel is that approximately 80% of the coal produced is used in the country of its production, in contrast to natural gas – 68% and oil – 42%. This fact can be explained by the lower energy density of coal compared to gas and oil, as well as significantly higher costs for its transportation [3-5] .

The main problem of coal use is slag formation and ash deposition, as well as the process of dust erosion of the tube surfaces of steam boilers and auxiliary thermal equipment [6,7] .

However, despite the above-mentioned "disadvantages", the role and significance of coal in global industry remains very significant.

1. Problem justification

The problem of wear resistance of the surfaces of heat exchange tubes of solid fuel steam boilers of domestic thermal power plants is very important, since it determines the reliability and duration of uninterrupted operation of power equipment.

Premature repair of elements of this nature requires considerable time and, especially in today's conditions, can significantly affect the stability of the power system of our country [8,9].

To date, computer-integrated control systems (CICS) of power units of thermal power plants use models that take into account the condition of the surfaces of heat-exchange tubes of steam boilers. The arguments of the model are the characteristics of the quality of solid fuel provided by the supplier of this fuel. However, in fact, the service life of screen and heat-exchange tubes differs significantly from the term obtained during modeling. This fact can be explained by the discrepancy between the abrasive component of coal at the time of unloading to the warehouse and its amount formed during coal combustion [8,9].

The solution to this problem is possible by improving the load control system of a solid fuel steam boiler with two independent channels for monitoring the condition of the surfaces of the heat exchange tubes of the boiler unit. In this case, one channel will detect the compliance of the chemical composition of the fuel with the specified one, and the other will detect the abrasive component in the flue gases after coal combustion.

Therefore, the purpose of this article is to improve the computer-integrated control system for the wear resistance of heat exchange tubes of a solid fuel steam boiler by introducing the distribution of solid fuel flow between control influences, unloading conditions, and solid fuel quality analysis .

2. KISU model of wear resistance of heat exchange surfaces

The first and main problem of wear resistance of heat exchange surfaces is the fact that the actual quality of solid fuel and the quality characteristics specified in the transport documents do not match. The lack of proper coal quality control forces the personnel of thermal stations to use fuel of inadequate quality, which leads to such negative consequences as abrasive wear of the surfaces of heat exchange pipes.

Previous studies show that it is possible to control the wear resistance of heat exchange surfaces by timely accounting for the abrasive impurity contained in the solid fuel. Such a system can be based on the distribution of the solid fuel flow between control influences and unloading conditions, as well as checking the quality of coal received from suppliers [10].

2.1. Transport problem of solid fuel supply

To construct the transport problem, Zaporizhia, Vuglehirska, and Burshtynska TPPs were selected, which operate on solid fuel and are respectively designated A_1, A_2, and A_3.

Table 1

Solid fuel consumption at TPPs

TPP	Electrical power, MW	Fuel 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

Suppliers are mines of the Donetsk coal basin (except Volynvugol and Lvivvugol). The case of a coal shortage on the domestic market was also taken into account. In this case, South Africa was chosen as the coal supplier.

The distances from the ports of the Odesa region (TIS port and Pivdenny port) to the selected TPPs are, respectively: to Zaporizhzhia - 555 km, to the city of Svitlodarsk (Vuglehirska TPP) - 845 km, and to the city of Burshtyn - 764 km.

The cost of transporting coal from the mines of the Donetsk Basin is shown in Table 2. Taking into account the relative cheapness of coal from South Africa (2,724.96 UAH per ton), as well as the location of the port of Pivdenny in relation to the selected thermal power plants, the scheme of importing coal from South Africa turns out to be cheaper and more profitable in terms of procurement.

The transport problem was solved taking into account the annual needs of the thermal power plant and the annual production of the selected mines [11].

Table 2

Cost of transporting coal per year from each mine, million UAH.

127.1801847	45.53740265	25.05064244	0.525	B_1	Volyn coal
744.1657721	733.8540063	112.856549	2.9655	B_2	Lviv Coal
66.7066685	19.85776548	242.3418564	0.998	B_3	Myrnograd-coal
101.2467087	34.75224867	350.532524	1.4165	B_4	Selydiv-coal
185.097695	65.47338679	610.4285685	2.5483	B_5	Dobropillya town
62.04281552	6.4617811	8.502343553	0.2515	B_6	Sosnivka
61.55068896	19.52414327	221.7148473	0.8565	B_7	Vugledar town
71.45735598	80.15046498	156.475962	0.9	B_8	Alexandria city
628.2408455	585.0998432	3084.581662	13.9575	B_9	Pavlohrad city
A_1	A_2	A_3	Z	$\Sigma A_n = \Sigma B_m = 24.42$	

The assessment of coal transportation for three selected TPPs (Zaporizhzhia, Vuglehirska, Burshtynska) showed that coal imports from South Africa, despite its lower quality and transportation time, can be a significant support in case of fuel shortage. The study shows that even taking into account the additional costs of coal enrichment to reduce ash content, it is still economically beneficial due to savings from reduced equipment wear. In addition, the optimal transportation plan determinesthe most efficient distribution of coal from different mines and the South African supplier to the TPP.

2.2. Mathematical model of the parametric scheme of a solid fuel boiler

The mathematical model is built on the basis of equations (2.1) and a parametric scheme (Fig. 1).

$$ZTPP = \begin{cases} W = W_{enrich}(Ad, V_{purch}) \\ L = L_{log}(x, V_{purch}) \\ C = C_{TPP}(Ad, T_{equip}) \\ T = T_{equip}(Ad, V_{purch}) \\ V = V_{purch}(Ad) \end{cases} \quad (2.1)$$

where $W_{enrich}(Ad, V_{purch})$ – a function describing the costs associated with the fuel enrichment process, depending on *Ad* and the purchase volume V_{purch};

$L_{log}(x, V_{purch})$ – a function describing the costs associated with logistics, depending on the volume of purchase (V_{purch});

$V_{purch}(Ad)$ – function of determining the required volume for purchase taking into account the abrasiveness of the fuel;

$C_{TPP}(Ad, T_{equip})$ – a function describing the costs of a thermal power plant associated with environmental pollution, repair and replacement of equipment due to the operation of highly abrasive fuel, depending on the operation time before an urgent stop for repair;

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

Taking into account the system of equations (2.1) and the CISU scheme, the system of equations of the mathematical model took the form:

$$\begin{cases} M_{sl} = M_f a_1 + M_{f_a} a_2 + M_{Ad} a_3; \\ M_{loss} = M_f b_1 + M_{f_a} b_2 + M_{Ad} b_3; \\ V_{res} = M_f c_1 + M_{res} c_2 + M_{en} c_3; \\ T_{op} = M_f d_1 + M_{f_a} d_2 + M_{Ad} d_3 + \\ \quad + M_{res} d_4 + M_{en} d_5; \\ N = M_f e_1 + M_{res} e_2 + M_{en} e_3. \end{cases} \quad (2.2)$$

where are a_n, b_n, c_n, d_m, e_n constant coefficients, $n = \overline{1,3}$; $m = \overline{1,5}$;

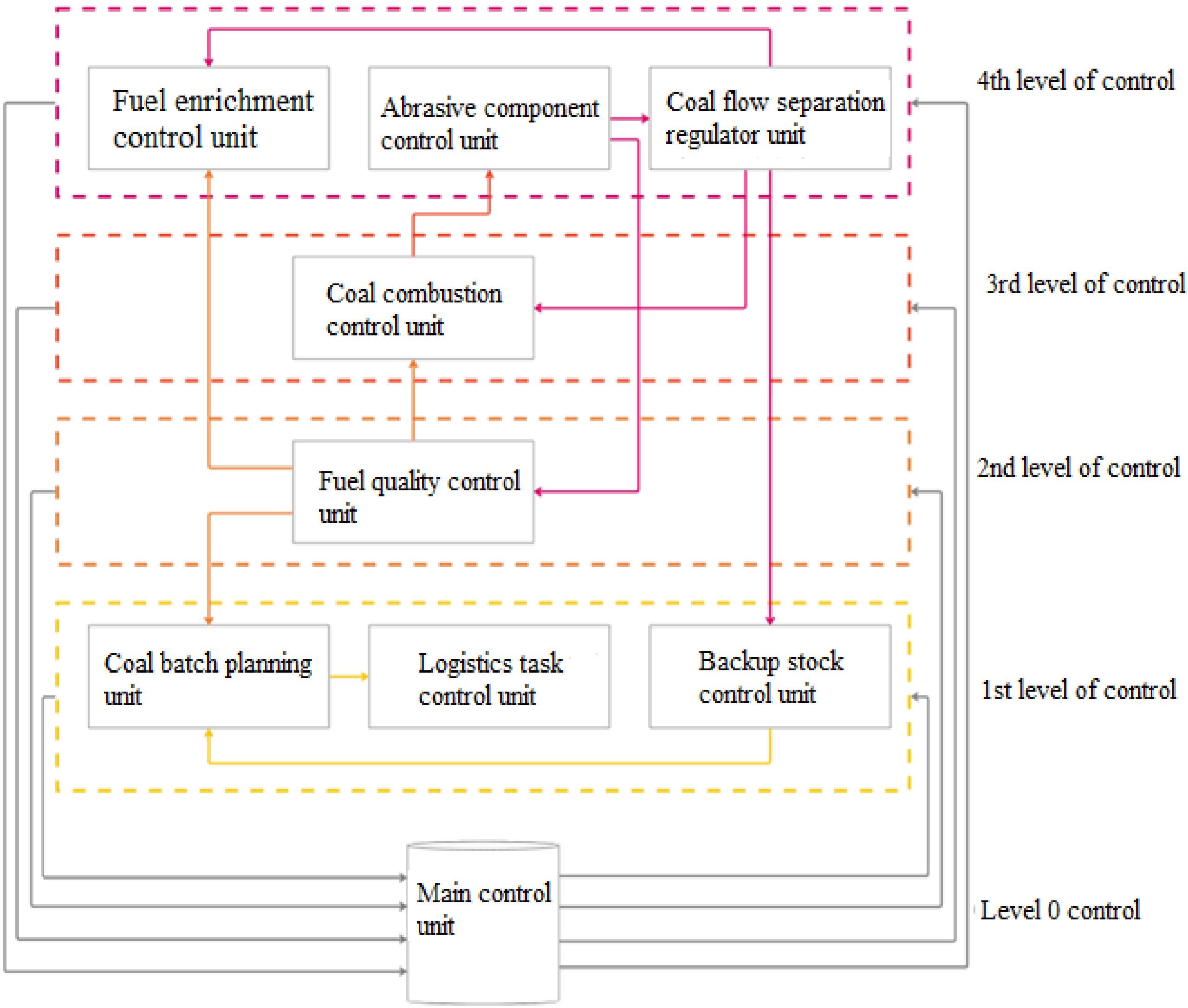

Fig. 1. Scheme of the KISU wear resistance of heat exchange surfaces of a solid fuel boiler

M_f – fuel consumption, kg/h;
M_{en}– consumption of enriched fuel, kg/h;
M_{res}– reserve fuel consumption, kg/h;
M_{f_a}– ash consumption, kg/h;
M_{Ad} – fuel ash content, %;
M_{sl}– consumption of the total amount of ash-slag pulp, kg/h;
T_{op}– operating time before replacing heat exchanger tubes, hours;
M_{loss}– carbon losses due to the discrepancy between the declared and actual ash content, which necessitates enrichment or use of reserves, kg/h;
V_{res}– fuel stock in reserve warehouse, t;
N – power of the station, MW.

The parametric diagram of a solid fuel steam boiler is built based on three main indicators: the current volume of solid fuel reserves, the operating time of heat exchange surfaces before repair or replacement, and the current flow of fly ash (Fig. 2).

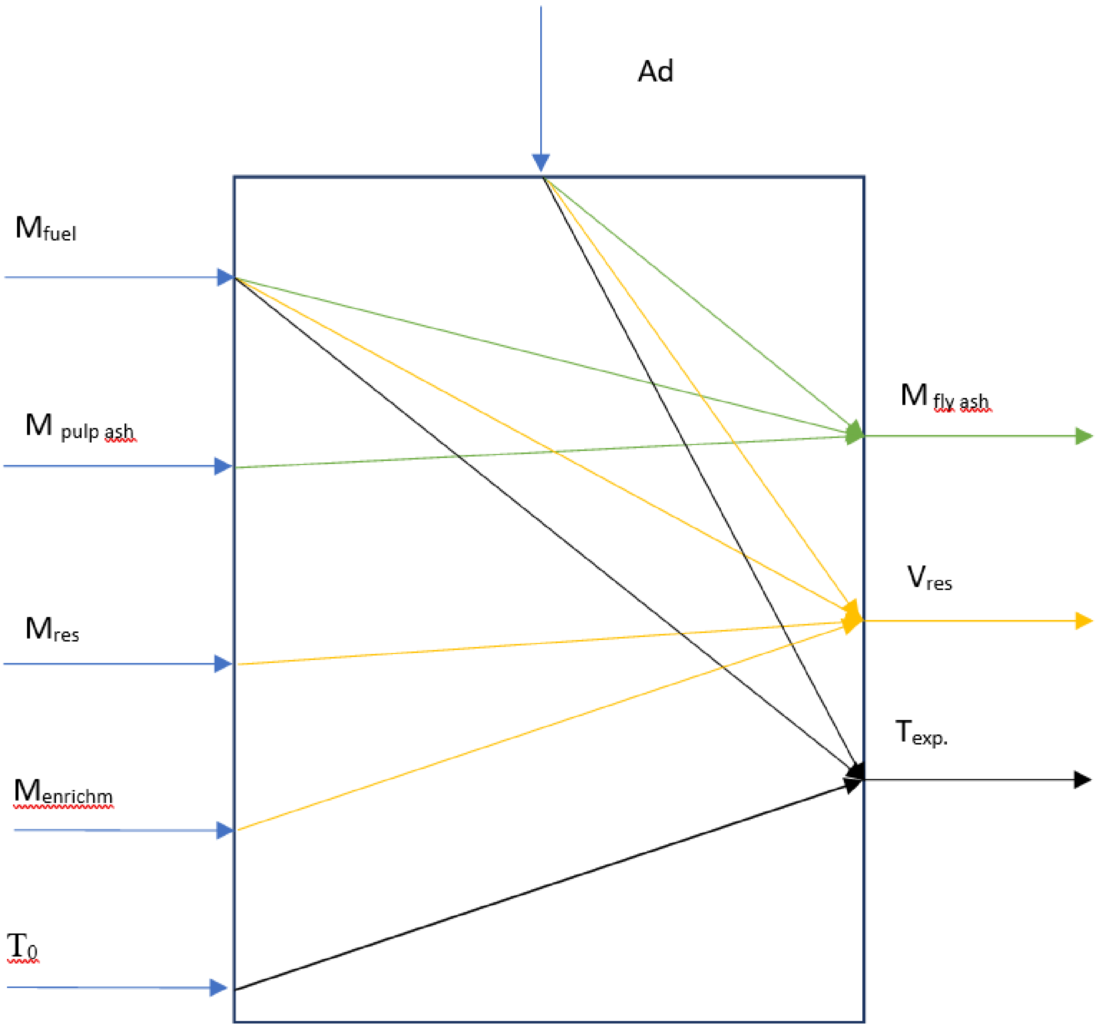

Fig. 2 Adapted parametric diagram of a solid fuel steam boiler

According to the parametric diagram of the boiler unit shown in Fig. 2, the system of equations (2.1) will take the form:

$$\begin{cases} M_{f\_a} = M_{sl} - F_{f\_a}(M_f, A_d) \\ V_{res} = V_0 - F_{en}(M_f, A_d, M_{en}) \\ T_{op} = T_0 - F_T(M_f, A^d,) \\ \quad M_{ash} - M_{sl} = 0 \end{cases} \tag{2.3}$$

where $M_{ash}$is the total ash consumption.

To study changes in the system over time, differential equations were constructed based on systems (2.2) and (2.3), which are given below:

$$\begin{cases} \frac{dM_{A_d}}{d\tau} = (M_{ash} + dM_{ash}) - \\ \quad -(M_{sl} + dM_{sl}) \\ \frac{dM_{A_d}}{d\tau} = dM_{ash} - dM_{sl} \end{cases} \tag{2.4}$$

Thus, the presented mathematical model of a steam boiler describes the relationships between the main parameters that characterize the wear resistance of heat exchange surfaces, namely: solid fuel and ash consumption, reserve stocks of solid fuel, and operating time before repair of heat exchange surfaces.

2.3. Fuzzy controller for controlling the wear resistance of heat exchange surfaces

To build a fuzzy controller for controlling the wear resistance of heat exchange surfaces, the following classification of solid fuel according to its quality was adopted (Table 3). Coal quality classes are divided according to the conditional clustering presented in [12] and can be classified as "Ideal", "Good" or other based on test results.

Table 3

Classification of solid fuels by degree of abrasiveness

Ad	Fuel quality class
0-5%	Ideal
5-9%	Good
9-16%	Normal
16-30%	Unsatisfied
30+%	Bad

Based on the defined coal quality classes, control influences were established that correspond to the defined solid fuel quality classes (Table 4).

Table 4

Correspondence of control influences to coal quality classes

coal quality class	*controlling influence*
Ideal	Transfer to reserve warehouse.
Good	Use for burning.
Normal	Partially enrich or mix with reserve.
Unsatisfied	Enrich, or enrich and mix with reserve.
Bad	Mix with the reserve, or use only the reserve.

Based on the defined solid fuel quality classes and their corresponding control influences, the proposed regulation scheme is shown below in Fig. 3.

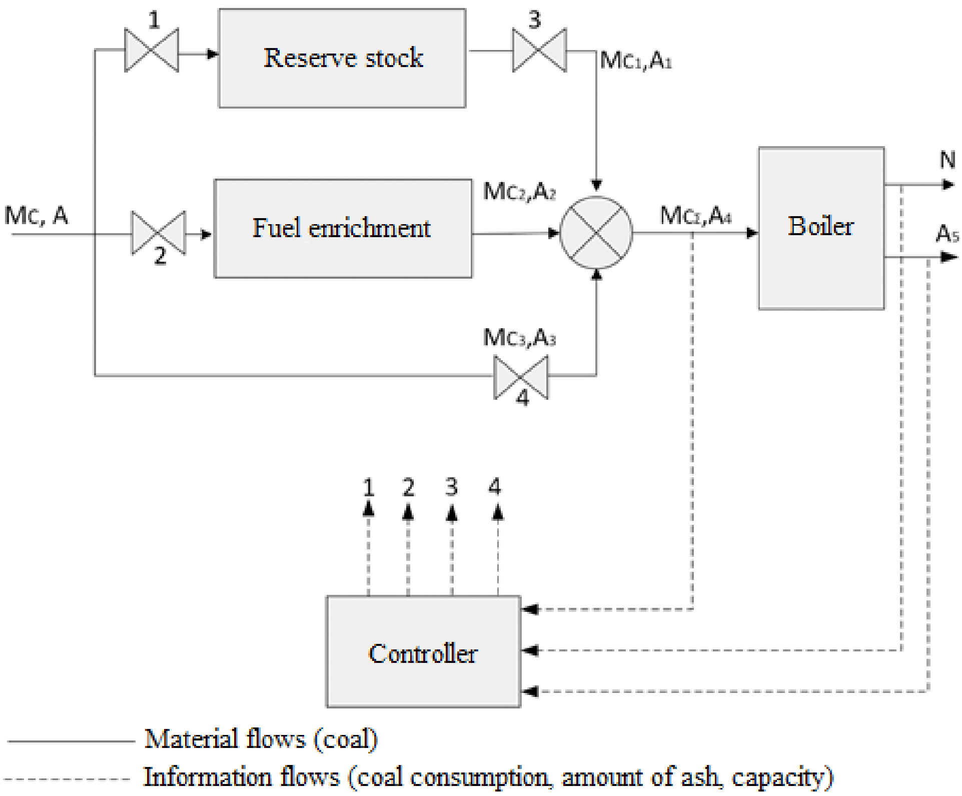

Fig. 3 Scheme of regulation of wear resistance of heat exchange surfaces

The next step was to build a fuzzy controller control system block, which is shown in Fig. 4.

The input values for the fuzzy controller were selected as the abrasiveness of coal (*Ad*) and the fullness of the reserve warehouse. As the control influence of the controller, the distribution of the coal flow by fractions in the following directions was taken: replenishment of the reserve warehouse (store) directly for burning (burning), enrichment (concentrator) and rejection of the current coal and use of the reserve (reserve _ out). The fuzzification of the variables *Ad* and the volumes of the reserve warehouse is shown in Fig. 5.

The control problem condition presented in Fig. 5 corresponds to the coal classes given in Table 3 and will influence the choice of control influence.

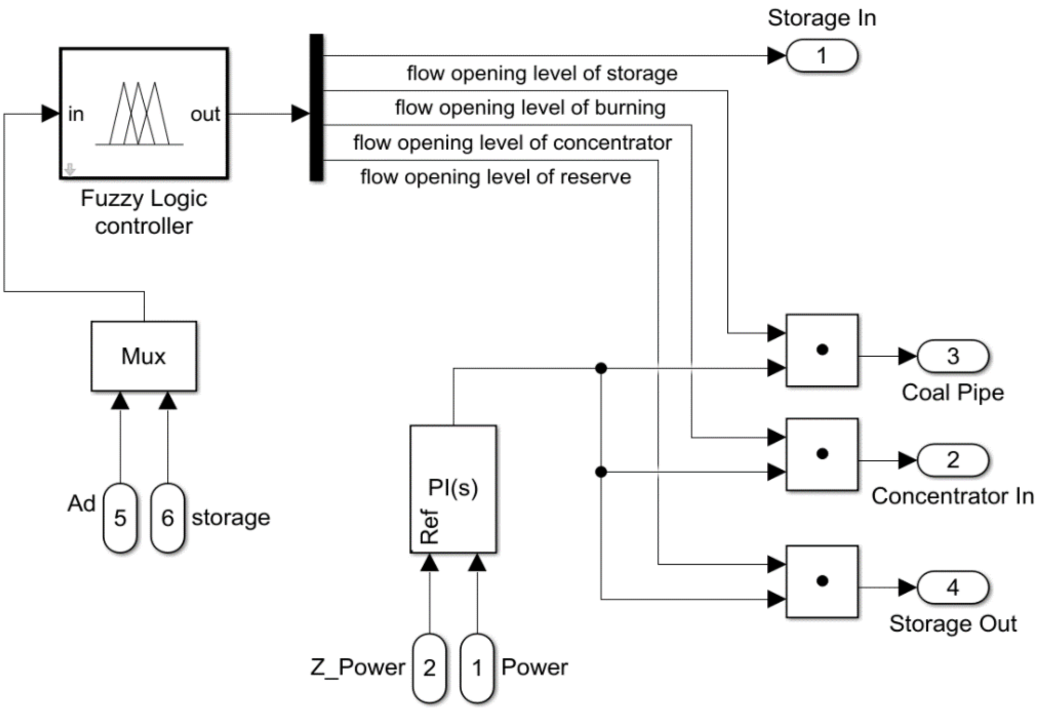

Fig. 4 Scheme of the control unit of the fuzzy controller

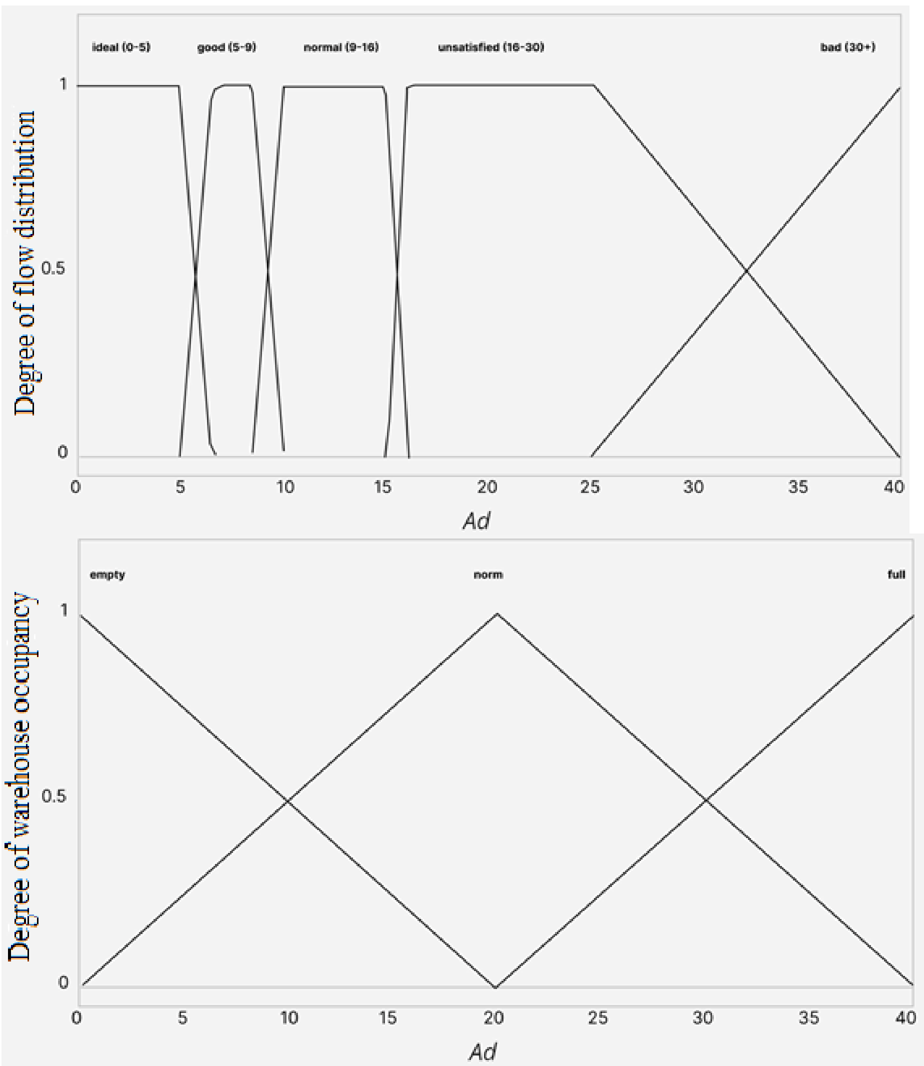

Fig. 5 Fuzzification of variables *Ad* and reserve stock volumes

The flow distribution rules are programmed as follows:

1. if (Ads is ideal (0-5)) and (store is full) then (store is small)(burning is large)(concentrator is small)(reserve_out is small);

2. if (Ads is ideal (0-5)) and (store is norm) then (store is normal)(burning is normal)(concentrator is small)(reserve_out is small);

3. if (Ads is ideal (0-5)) and (store is empty) then (store is large)(burning is normal)(concentrator is small)(reserve_out is small);

4. if (Ads is good (5-9)) and (store is full) then (store is small)(burning is large)(concentrator is small)(reserve_out is small);

5. if (Ads is good (5-9)) and (store is norm) then (store is small)(burning is large)(concentrator is small)(reserve_out is small);

6. if (Ads is good (5-9)) and (store is empty) then (store is normal)(burning is normal)(concentrator is small)(reserve_out is small);

7. if (Ads is norm (9-16)) and (store is full) then (store is small)(burning is large)(concentrator is small)(reserve_out is small);

8. if (Ads is norm (9-16)) and (store is norm) then (store is small)(burning is large)(concentrator is small)(reserve_out is small);

9. if (Ads is norm (9-16)) and (store is empty) then (store is small)(burning is large)(concentrator is normal)(reserve_out is small);

10. if (Ads is unsatisfied (16-30)) then (store is small)(burning is normal)(concentrator is normal)(reserve_out is normal);

11. if (Ads is bad (30-40)) then (store is small)(burning is small)(concentrator is normal)(reserve_out is large).

And the condition of the problem shown in Fig. 6 and Fig. 7 will affect the degree of replenishment and use of the TPP reserve.

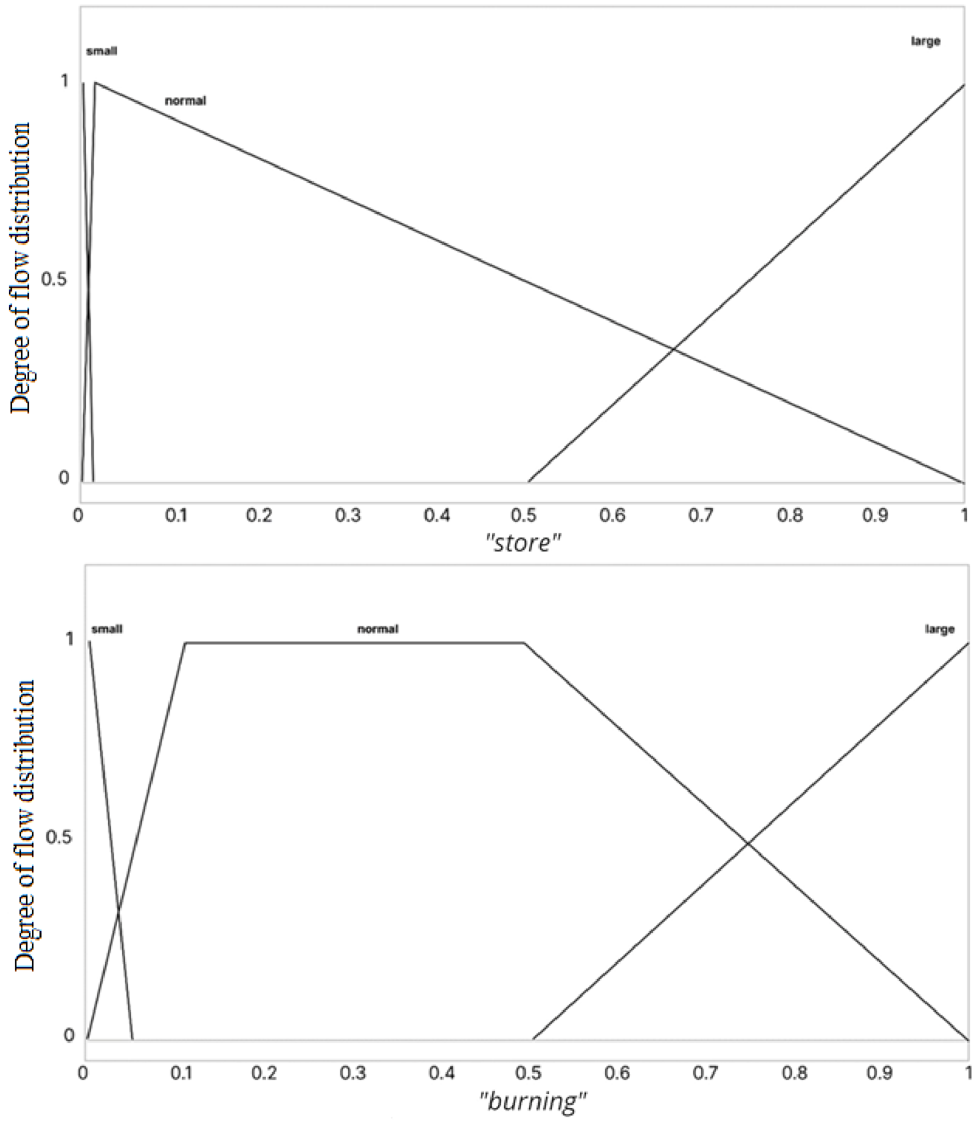

Fig. 6 Defuzzification of the control influences “store” and “burning”

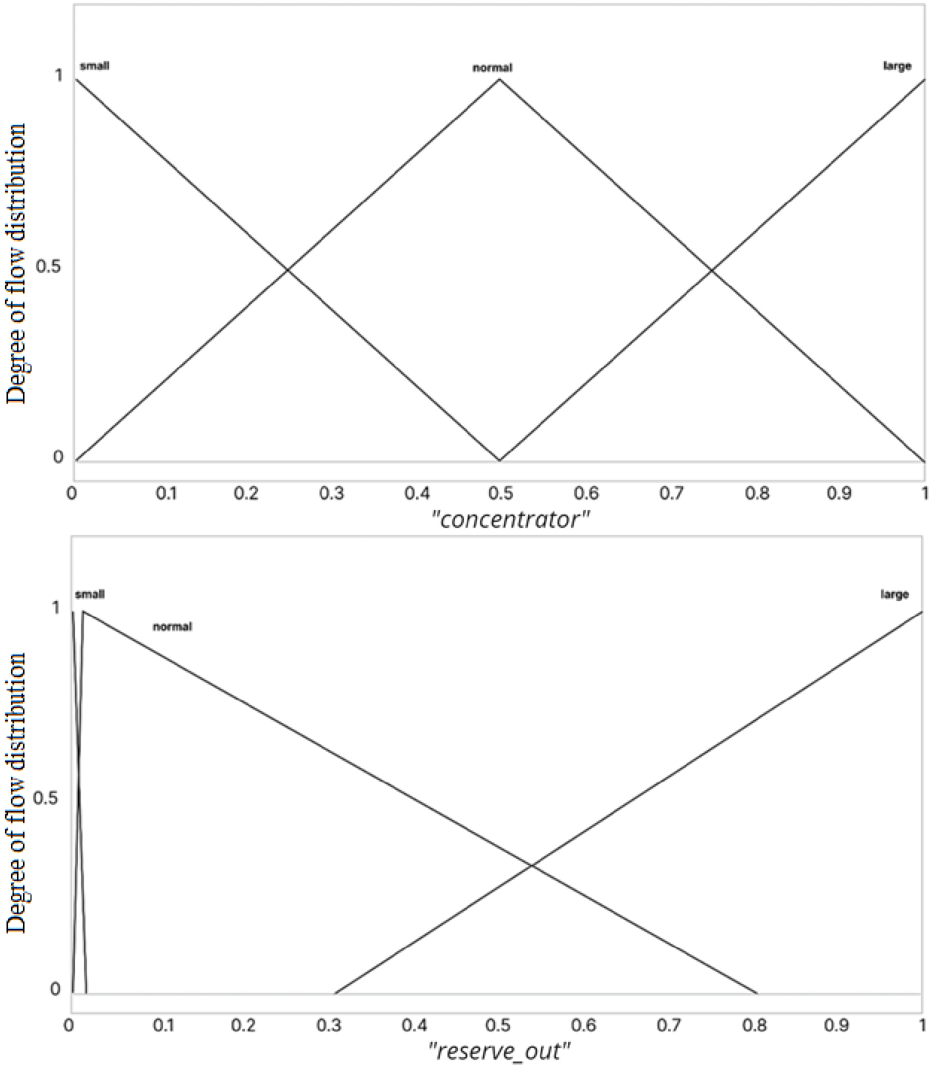

Fig. 7 Defuzzification of the control influences "concentrator" and "reserve_out"

Using “ Rule Viewer ” the settings of the programmed rules were checked. The results of the check are presented below:

- at *Ad* = 5%, and the reserve warehouse occupancy is 74.7%: the reserve warehouse occupancy rate is 0.438; burning – 0.561;
- at *Ad* = 0.238%, and the reserve warehouse occupancy is 26.1%: the reserve warehouse occupancy rate is 0.501; burning – 0.5;
- at *Ad* = 7.2%, and the reserve warehouse occupancy is 71.8%: the reserve warehouse occupancy rate is 0.0161; combustion – 0.814;
- at *Ad* = 8.81%, and the reserve warehouse filling rate is 10%: the reserve warehouse filling rate is 0.418; combustion – 0.511; enrichment – 0.35;
- at *Ad* = 15.8%, and the reserve warehouse is 100% full : the reserve warehouse filling degree is 0.0146; combustion – 0.36; enrichment – 0.285;
- at *Ad* = 39.1%, and the reserve storage is 100% full : the reserve storage filling rate is 0.0175; combustion – 0.0183; enrichment – 0.331; reserve fuel use – 0.673.

2.4. Simulation of the operation of a fuzzy controller at different degrees of fuel abrasiveness

The developed fuzzy controller works by fractional distribution of solid fuel flow directions. Of significant interest is the operation of the controller at different levels of abrasive materials contained in coal.

Modeling of the regulator operation was carried out for cases when *Ad* = 35% at a warehouse occupancy of 90% and when *Ad* continuously increases from 14% to 35% at a warehouse occupancy of 100%.

The case with a constant value of *Ad* = 35% (Fig. 8 and Fig. 9) shows that most of the solid fuel flow to the furnace will come from the reserve, while the delivered coal will be distributed between the furnace and enrichment.

For the case of a variable value of *Ad* , namely a constant increase from 14% to 35%, the scheme and results are shown in Fig. 10 and Fig. 11, respectively.

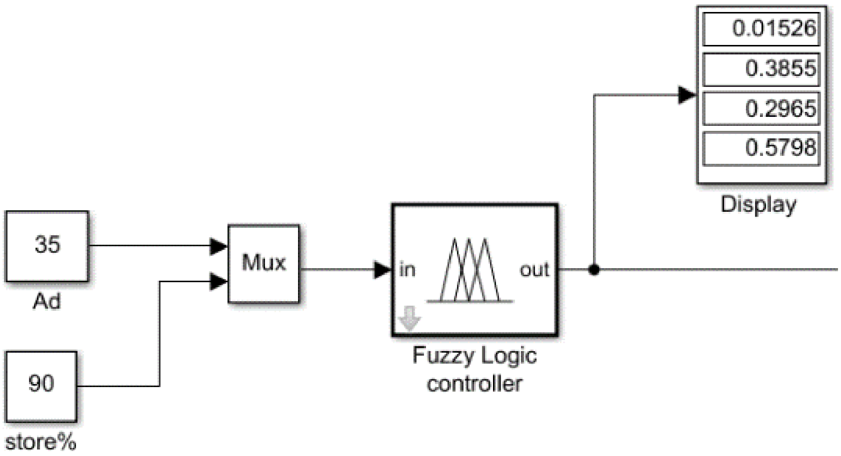

Fig. 8 Coal flow control scheme with a constant abrasive component of 35%

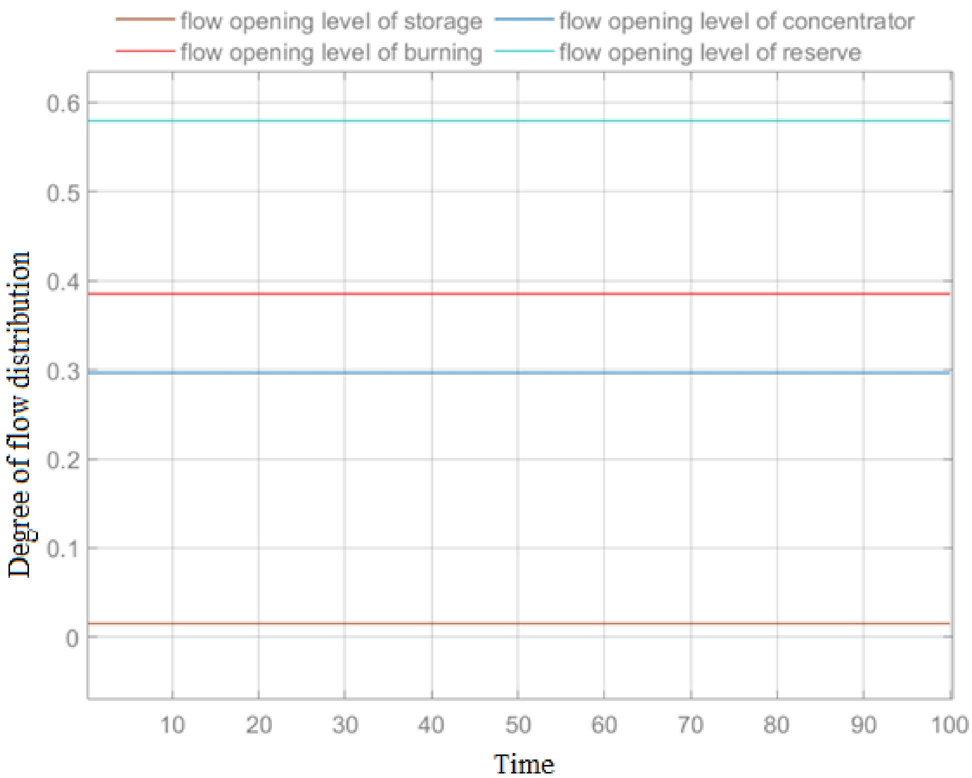

Fig. 9 Graph of results for the scheme from Fig. 8

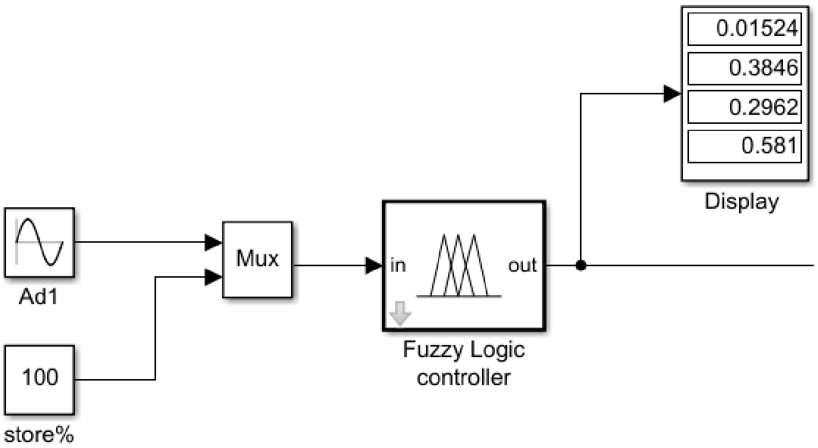

Fig. 10 Coal flow control scheme with increasing abrasiveness from 14% to 35

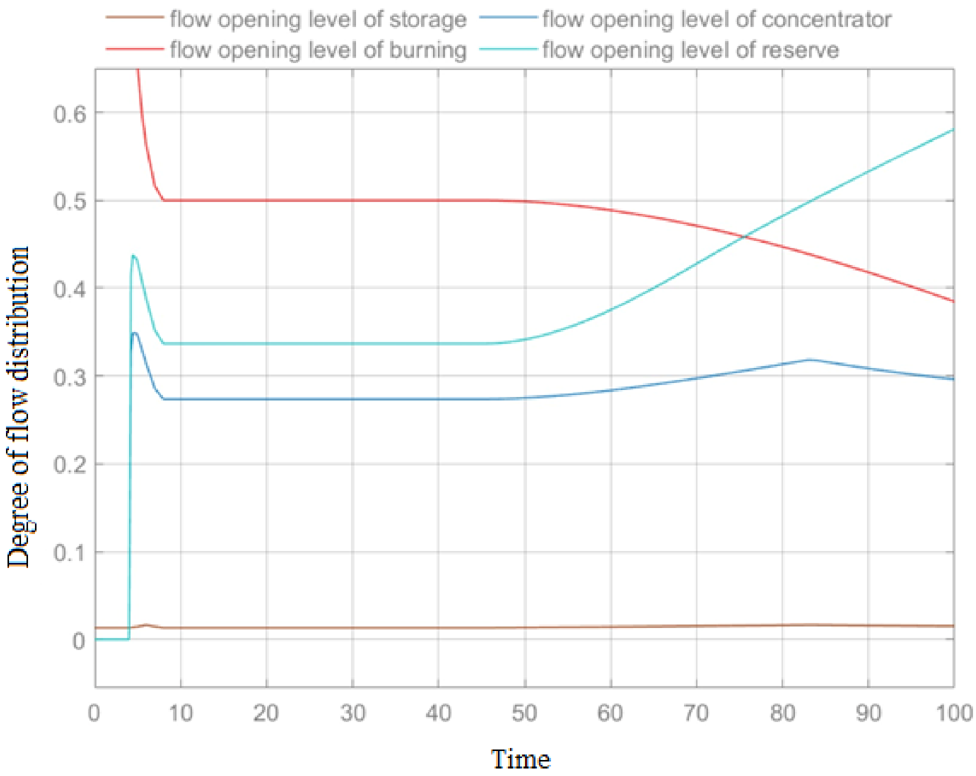

Fig. 11 Results graph for the scheme from Fig. 10

The results from Fig. 11 can be commented on as follows:

- At the initial *Ad* = 14% (system operating time $t_0 = 0$ s), almost the entire fuel flow is directed to combustion.
- With the system operating 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 thermal coal is sent for combustion, mixing with reserve fuel, and the rest for enrichment.
- At the end of the experiment ($t_2 = 100$) at *Ad* = 35%, the largest share of the burned fuel will be thermal coal from the reserve. In this case, coal from the supplier will be partially burned and partially sent for enrichment.

From the results of the simulation, it can be concluded that with a consistent increase in the content of abrasive material in solid fuel, the flow rate of reserve fuel increases, and the flow rate of ash fuel decreases. Thus, this fact can contribute to reducing the erosion rate of heat exchange surfaces of the steam boiler from the flow of abrasive material during fuel combustion.

Conclusion

This article considers the problem of wear of heat exchange tubes of solid fuel steam boilers and proposes a method for improving their wear resistance using a computer-integrated control system. The developed mathematical model allows taking into account variable parameters of fuel quality, in particular its abrasiveness, which significantly affects the duration of operation of boiler equipment.

The simulation modeling confirmed the effectiveness of the proposed system, which allows to reduce wear of heat exchange surfaces, optimize fuel consumption and reduce operating costs. The use of two independent fuel quality control channels contributes to more precise regulation of the combustion process and minimizes the negative impact of low-quality fuel.

The results obtained can be used to further improve automatic control systems for boiler units, which will contribute to increasing the efficiency of thermal power plants and reducing their environmental impact.

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Комп'ютерно-інтегрована система управління зносостійкістю поверхонь теплообмінних труб твердопаливних котлоагрегатів з розподілом потоків вугілля між керуючими впливами

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Анотація. *У статті розглянуто проблему зносостійкості теплообмінних труб твердопаливних парових котлів, що є важливим аспектом підвищення ефективності та надійності енергетичного обладнання. Запропоновано комп'ютерно-інтегровану систему управління, яка враховує змінні параметри якості палива, зокрема його хімічний склад та абразивність. Використання такої системи дозволяє здійснювати моніторинг якості палива в режимі реального часу, що є критично важливим для мінімізації процесів ерозії та продовження терміну експлуатації котельного обладнання.*

Основною особливістю запропонованої моделі є використання двох незалежних каналів контролю якості твердого палива. Перший канал відповідає за визначення відповідності хімічного складу палива заявленим характеристикам, що дозволяє прогнозувати рівень утворення відкладень і забруднень. Другий канал здійснює аналіз вмісту абразивних частинок у димових газах після спалювання вугілля, що безпосередньо впливає на швидкість зношення теплообмінних поверхонь. Завдяки інтеграції цих двох підходів система забезпечує точне та адаптивне регулювання режимів роботи котла, мінімізуючи вплив низькоякісного палива на загальну продуктивність котлоагрегату.

Запропонована система також включає математичну модель для оцінки довговічності теплообмінних труб залежно від характеристик палива та умов експлуатації. Реалізовано алгоритм розподілу

потоків палива між основними керуючими впливами, що дає змогу оптимізувати процес горіння, зменшити зольність відходів та підвищити ефективність використання енергетичних ресурсів.
Результати імітаційного моделювання підтвердили ефективність розробленої системи: вдалося суттєво зменшити швидкість ерозії теплообмінних труб, оптимізувати споживання палива та знизити витрати на технічне обслуговування. Використання такого підходу дає змогу зменшити простої котельного обладнання, підвищити стабільність роботи енергетичних систем і знизити негативний екологічний вплив.
Запропонована система управління може бути використана як основа для подальшого вдосконалення автоматизованих рішень у сфері контролю зношування та ефективності роботи твердопаливних котлів. Її впровадження дозволить значно підвищити надійність енергетичних установок, знизити експлуатаційні витрати та продовжити термін їхньої служби, що є актуальним завданням для сучасної енергетики.

Ключові слова: *твердопаливний паровий котел, якість твердого паливо, комп'ютерно-інтегрована система управління, зносостійкість теплообмінних поверхонь, абразивність твердого палива.*

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