

THE COAL QUALITY CICS THAT INCREASES THE WEAR RESISTANCE OF HEAT EXCHANGER TUBES

Submitted: 14th October 2022; accepted: 29th September 2023

Maksym Grishyn, Kostiantyn Beglov

DOI: 10.14313/JAMRIS/1-2024/2

Abstract:

The paper discusses the threat of decommissioning to the thermal power plant (TPP) heat exchanger tubes because of erosion and develops a computer-integrated control system (CICS) for the process of distribution of steam coal flows with different indicators of abrasive materials content, which is based on fuzzy logic.

The problem of rapid decommissioning of TPP heat exchangers, particularly abrasive damage to furnace screen tubes, economizer, superheater, etc. This may indicate a discrepancy between the expected fuel ash content and the actual one, as well as a high content of abrasive impurities in steam coal.

The work aims to develop a CICS of the wear resistance of the heat exchange surface of a steam boiler of a coal-fired power plant by measuring and fuzzy control of the content of abrasive impurities in steam coal.

The problems of damage to the equipment of the TPP boiler are investigated, and a system for controlling the wear resistance of the surface by automatic fuzzy control of the quality of coal is developed. The results were investigated during coal preparation and combustion in the furnace of a thermal power plant to investigate the effectiveness of the proposed fuzzy controller. The model results confirm the feasibility of the fuzzy control method for the system with different coal quality parameters.

Keywords: *Automatic control system, Fuzzy control, Coal-fired power plants, Variable quality of coal, Fuel enrichment, Wear resistance of the heat exchanger*

1. Introduction

Despite the constant increase in the use of renewable energy sources to cover the demand of modern energy systems, according to [1, 2], most of the world's electricity is produced by classical thermal power plants (TPP), in particular, the main resource for electricity production is coal (about 36.7%). Thus, the problems that arise from using fuel are still relevant today. In particular, coal with a high content of abrasive impurities during combustion creates erosive wear of the heat exchange surface tubes caused by the movement of solid particles entrained in the flue gas, which increases the risk of premature decommissioning of this particular equipment. Further, in this paper, it will be referred to as abrasive wear.

The problem of quality is the problem of fluctuations in the composition of coal used for combustion, namely: high content of abrasive material in the ash impurity of coal or a discrepancy between the specified ash content (declared by the supplier) and the actual one. Thus, unscrupulous suppliers who declare a small ash content can deliver bad fuel to TPPs.

Currently, power plant management has the opportunity to solve the problem of low-quality fuel in one of two ways: to try to enrich low-quality fuel [3,4] or to mix it with high-quality fuel in a reserve warehouse. However, for the successful application of these solutions, it is necessary to understand how useful the fuel enrichment will be, taking into account the losses during enrichment, enrichment costs, and transport delay, and it is also necessary to know the exact current coal quality to effectively manage the fuel quality.

Since modern power plants are not equipped with a laboratory for a detailed investigation of the abrasive content of ash impurities, there is also a problem with how to calculate detailed coal quality indicators for accurate assessment of the wear resistance of the heat exchange surface of the steam boiler. Additional difficulties arise due to the impossibility of premature shutdown of the power plant to check the condition of the equipment. It is also worth noting that it is difficult to unambiguously divide the quality of coal into categories to distribute the flows between the furnace, replenishment of the reserve stock, enrichment equipment, and the need to attract stocks from the reserve for mixing and combustion in the furnace. Therefore, it is advisable to create advanced control systems for power plants operating under conditions of changing the quality of steam coal based on fuzzy control principles.

This work describes the development of a power plant automation system to enable the detection of inconsistencies in the quality of energy fuel and to implement a fuzzy controller for the distribution of fuel flows depending on their quality. Section 2 presents a literature review of current research issues and sets the main objectives of this work. The third section is devoted to the development of a fuzzy control system for the wear resistance of the heat exchange surface of a steam boiler of a coal-fired power plant by controlling the quality of steam coal at the expense of fuel flow distribution, as well as modeling the action of the control device at various coal

quality indicators, and the study of the effectiveness of the fuzzy control system.

The regulation was built on fuzzy logic because the division of coal quality into five conditional classes was proposed, but it is impossible to divide the classes by abrasiveness indicators. The fourth chapter is presented in the form of conclusions and suggested directions for further research.

Modern power plants, with their intricate operational dynamics, often grapple with uncertainties ranging from fluctuating fuel quality to variable environmental conditions. Traditional control systems, structured around rigid mathematical frameworks, sometimes falter in the face of these nonlinearities and ambiguities. Fuzzy logic stands out as a superior alternative, adeptly managing such uncertainties through its inherent design rooted in linguistic variables and fuzzy set theory. This allows for more flexible, intuitive decision-making that mirrors human reasoning patterns, making it especially valuable in translating the vast experiential knowledge of power plant operators into actionable control algorithms. Furthermore, its adaptive nature ensures resilience in changing conditions, ensuring that power plants maintain optimal performance even amidst unforeseen disturbances.

2. Related Works

The current trends of research in modeling and management science remain relevant to many fields of endeavor [5]. Despite special attention being paid to such areas as soft computing, uncertainty, bibliometrics, neural networks, etc., the energy field is not an exception. Nowadays, several studies have been carried out on various technologies for assessing the harmful effects of low-quality fuel on the wear resistance of the heat exchange surface [6,7], predicting the consequences, as well as automation of installations and technological complexes to maintain stable operation of the power plant.

Besides, [8] pays much attention to the description and modeling of plants as a whole and their parts (heat exchangers, turbines, boilers, etc.), and [9] considers such control methods as PID-law, fuzzy logic control, and others. These materials examine methods of maintaining the stability of power systems by increasing the fuel supply, but the task of significantly reducing the abrasive wear of the heat exchange surface is not solved, which can lead to unpredictable consequences in the form of the premature shutdown of the power unit for unscheduled repairs, which will be a critical load on the overall power system.

In [10], the issues of ash impurity of fuel, its abrasive effect on TPP equipment, and assessment of the efficiency of fuel enrichment to reduce the risks of TPP costs in case of urgent repairs were considered. TPP operation is presented in the form of a model, which was expressed in the sum of total financial and other costs associated with malfunctions: repair and replacement of equipment, additional fuel purchase, etc. Under the condition of fuel enrichment, the savings in TPP costs are expressed during the lifetime of the equipment, including the costs of enrichment [11, 12].

It was concluded that it would be more cost-effective for TPPs to purchase and set up coal preparation equipment than to shut down the power unit for scheduled or unscheduled repairs.

It would be possible to abandon low-quality fuel in advance and switch to reserve fuel to prevent these risks from approaching, but the task is significantly complicated by the fact that it is impossible to be sure of the quality of the imported steam coal or to measure the change in abrasive damage of the heat exchanger surface during combustion to analyze the actual wear resistance [13, 14]. Even if there was such an opportunity to learn in real-time about the damage to the heat exchange surface during the combustion of steam coal, TPPs are traditionally not equipped with a laboratory to study the quality of coal composition. Additional difficulties are also imposed by the approximate (not exact) determination of the percentage of certain components in the composition of raw materials. Thus, to successfully solve this problem, it was necessary to create a computer-integrated control system (CICS) for the process of coal fuel flow distribution, regardless of the content of abrasive material in the ash impurity, based on fuzzy logic.

Much attention in [15, 16] is paid to control based on fuzzy logic, namely, a control method for regulating power and enthalpy in the boiler of a 765 MW coal-fired thermal power plant is presented, and fuzzy boiler power control by a steam regulating valve.

The application of fuzzy logic in control systems, especially within thermal power plants, has been a topic of significant interest and study in recent years. As the energy sector faces increased challenges from varying conditions and the need for optimized performance, fuzzy control systems present an adaptable solution.

Kondratenko and Kozlov's exploration into generating rule bases for fuzzy systems delves into the use of Modified Ant Colony Algorithms, demonstrating the capability of such algorithms to enhance the performance and accuracy of rule formulations [17]. Furthermore, a 2022 publication by Kozlov et al. accentuates the importance of fuzzy logic in managing the complexity of the pyrolysis process, especially when dealing with municipal solid waste of varying composition [18]. This underscores the adaptability of fuzzy systems in handling heterogeneous inputs, a situation frequently encountered in power plants.

A different angle to the study of fuzzy logic in power facilities was presented by Satyanarayana et al. in 2014, who offer insights into automatic generation control in power plants. Their work comparatively evaluates the performance of PID, PSS, and Fuzzy-PID controllers, illuminating the unique benefits of the Fuzzy-PID in achieving better stability and response times [19].

The environmentally conscious facet of power generation is highlighted by Kozlov et al., who emphasize the development and optimization of "Green Fuzzy Controllers" specifically tailored for reactors in specialized pyrolysis plants [20]. Their approach marries the principles of sustainable power generation with the adaptability of fuzzy logic.

[21] dives deeper into the parametric optimization of fuzzy control systems. By harnessing hybrid particle swarm algorithms equipped with an elite strategy, their research sets a new benchmark in optimizing the performance of fuzzy control systems, opening new doors for real-time adaptive control in power plants.

Papers [22, 23] emphasize the importance of fuzzy control systems in managing temperatures, particularly during pyrolysis processes. Their research underscores how fuzzy PID control systems can enhance thermal behaviour analysis, offering improvements in temperature regulation and overall system stability.

The main purpose of the paper was to develop and study a CICS for the wear resistance of the heat exchange surface of a steam boiler of a coal-fired power plant by controlling the quality of coal by distributing the flow of coal supplied for combustion.

To achieve this goal, the following tasks were formulated:

- to develop a model of the measuring channel of abrasive material content in steam coal for a CICS;
- to develop a mathematical model for detecting inconsistency of fuel quality indicators during its combustion in the TPP furnace;
- to develop a control device based on fuzzy logic to control the wear resistance of the heat exchange surface by controlling the quality of coal by distributing the flow of coal sent to the furnace; and
- to simulate the operation of the closed-loop control system at different indicators of coal abrasiveness.

3. Development of a Fuzzy CICS of Wear Resistance of the Heat Exchange Surface of a Steam Boiler of a Thermal Power Plant by Controlling the Quality of Steam Coal

Before developing the CICS, it was necessary to consider, and model the measuring channel of steam coal quality, and analyze and form mathematical models of the control object.

4. Development of the Model of Measuring Channel of Abrasive Material Content in Steam Coal for the CICS

Usually, TPPs are not equipped with a laboratory to test each batch of coal, but from time to time, the quality of purchased fuel may differ from the indicator in the documents, and it was necessary to develop a method for determining the ash content of the fuel.

Three methods of determination were formulated:

- 1) Based on the power unit capacity reduction at a steady coal consumption, i.e. with an active reduction of electricity generation, it is likely that the carbon mass in the fuel is much lower than specified.

- 2) Based on increased fuel consumption at constant unit capacity. If to maintain the load of the power unit, it is necessary to increase the consumption of combusted fuel; it also indicates a decrease in the carbon content of the coal batch. In this method, fuel consumption is determined using automatic conveyor scales used at TPPs.

- 3) By determining the mass of ash in the ash collectors when using electrostatic precipitators or separators in the pipes of TPPs, to analyze with their help and knowledge of the technical characteristics of the equipment whether more ash is received in the ash collector than is permissible.

These methods were considered in more detail.

The first method:

Let E in (1) be the electricity generation under the condition of ideal fuel. $E_{n_{SiO_2}}$ is the electricity generation, including the declared n_{SiO_2} index, where n_{SiO_2} is the content of abrasive material in coal.

$$E_{n_{SiO_2}} = \eta_{TPP} * 24 * N_{turb} * E(1 - n_{SiO_2}), \quad (1)$$

where

N_{turb} – turbine power;

η_{TPP} – efficiency of thermal power plants;

E_{fact} – actual electricity generation.

If $E_{fact} < E_{n_{SiO_2}}$, then the actual abrasiveness of the fuel exceeds the declared one.

The disadvantage of this method is that it has low accuracy. At the same time, even an approximate indicator of the actual abrasiveness of the material is unknown.

In addition, the main problem with this method is that most boiler units have a fuel supply regulator, which does not allow for the reduction of the power of turbines [9].

According to the disadvantages of the main problem of the first method, **the second method** is that one could try to determine if the actual fuel consumption increases from that which should be at the declared abrasiveness.

In this method, the main drawbacks are similar to the first method. This method of calculating abrasiveness is approximate, and it was very difficult to understand the actual ash content and abrasiveness of the fuel.

In this case, neither method was very effective, but they had a place to check their data.

Therefore, **the third method** was adopted as the main way to calculate the ash content of the material.

In [10], “Zaporizhzhia TPP” in Energodar city (Ukraine) was considered prototype A.

Without laboratory analysis, it is impossible to say exactly what part of the fuel is combustible mineral content and what part is an abrasive material. Given that most of the combustible mineral content simply burns, and abrasive material accumulates on the filters and in the ash dump, it was assumed that the actual ash content during combustion will be the actual abrasiveness. That is, in the future, these concepts will be identified.

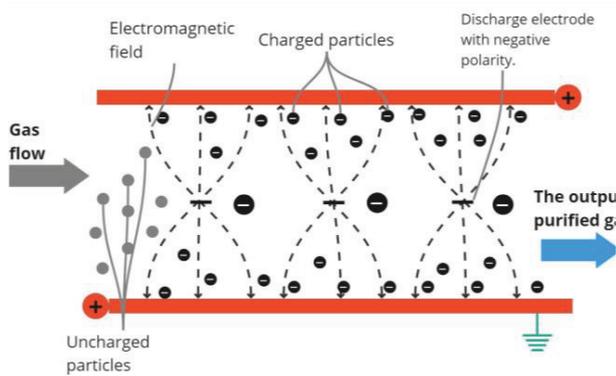


Figure 1. Schematic drawing of the electrostatic precipitator

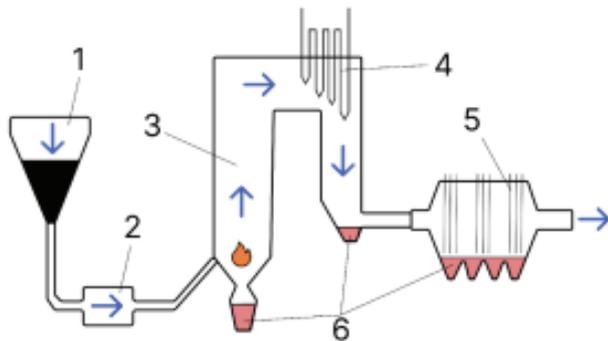


Figure 2. Dynamics of ash accumulation in the combustion process. (1 – coal bunker; 2 – coal mill; 3 – furnace; 4 – superheater tubes; 5 – filters; 6 – places of ash accumulation in ash collectors: furnace, economizer, and smoke filters)

This was done to save time on laboratory tests of unburned fuel residues. Further, the most pessimistic scenario assumes that the ash content is an indicator of the abrasiveness of steam coal.

Further, the method of calculating the actual ash content (abrasiveness) of the fuel was considered.

According to [24], “Zaporizhzhia TPP” uses electrostatic precipitators in its production, which is a more modern and efficient way to collect ash [25]. Usually, the efficiency is about 97–98%, in contrast to outdated wet ash collectors (Venturi scrubbers with remote droplet separator) from the 60s and 70s with a filtration efficiency of about 50%.

Then, it became necessary to analyze the difference between the actual amount of ash obtained during fuel combustion and the amount that should have been obtained according to the declared quality.

The difficulty of measuring the consumption of mineral impurities present in coal fuel is that the ash residue formed after combustion does not move in a single stream but accumulates in some characteristic places. This is facilitated by ash collectors.

According to the ash collecting schemes of TPPs, in particular Figure 2, it was summarized that it is possible to estimate the amount of ash in ash collectors of three types: in the furnace, in the economizer ash collector, and the chimney filter ash collector.

The State Statistics Service of Ukraine regularly records the amount of greenhouse gas emissions using a formula approved by the Ministry of Environmental Protection and Natural Resources of Ukraine. This was used to calculate emissions from regular fuel combustion. Thus, from [26–28], the following is formulated in (2):

$$Em_{CO_2i} = AC_i * LCV_i * EFi * Of_i \quad (2)$$

where:

Em_{CO_2i} – CO_2 emissions from fuel combustion of type (i), [tons CO_2]

AC_i – activity data: the amount of fuel combustion of type (i), [tons or thousand m^3].

LCV_i – is the lower calorific value of fuel of type (i) [T]/t or T]/thousand m^3].

EF_i – is the CO_2 emission factor for fuel of type (i) [t CO_2 /T].

Of_i – is the oxidation factor for fuel of type (i).

The main combustion products according to [13, 26], which need to be paid attention to (listed as the main ones) are CH_4 , N_2O , and CO_2 .

The following emission volumes were obtained for TPP A:

CO_2 – 4,519,919.60 m^3 ;

N_2O – 411.09 m^3 ;

CH_4 – 373.10 m^3 ;

Total: 4,520,703.79 m^3 /h.

In the case of simultaneous operation of at least four filters, it was necessary to find filters with a capacity of 1,309,880 m^3 /h.

Filters that meet the following requirements are EGV2-70-12-6-6, EGV2-70-12-6-7, EGV2-70-12-6-8. The conditions of 100% ash capture were considered to build the model.

For further construction of the technological model, the schematic drawing of ash and slag removal from the principle of [8, 14], Figure 3 is considered

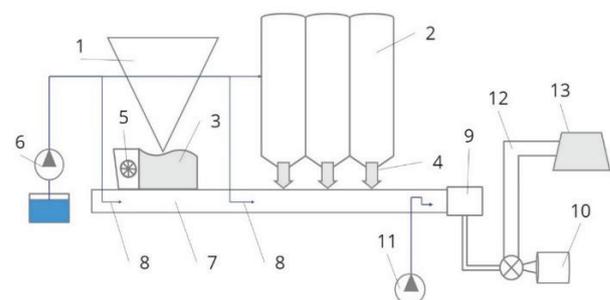


Figure 3. Schematic drawing of ash and slag removal: 1 – boiler furnace chamber; 2 – ash collector; 3 – bath with a scraper conveyor for continuous ash removal; 4 – ash flushing apparatus of the ash collector; 5 – slag crusher; 6 – flushing pump; 7 – ash channel; 8 – sluice nozzle; 9 – receiving hopper of slurry with metal catcher; 10 – baghouse pump; 11 – drainage pump; 12 – slurry pipelines; 13 – ash dump

to investigate other places of ash accumulation during fuel combustion.

The above drawing shows that the ash settles in the ash disposal channel during combustion. From the filter and economizer, the ash falls directly into the ash collector and then, using a conveyor, into the booker and further into the ash disposal area. With the help of conveyor scales, it is possible to determine the mass of material that has not burned, but there was still a problem with ash that remains directly in the furnace.

According to the technological procedure of ash removal [14], the fly ash from the ash collectors mixes with ash and slag that flows out of the furnace through the ash channel and, together with the process fluid, creates ash and slag slurry, which goes to the ash disposal area through the slurry pipeline. It would be possible to measure the slurry flow rate in the slurry pipeline and, when deducting the technical fluid, to understand the ash flow, its relation to the fuel flow, and the difference between the actual and the declared ash content. However, more relevant is the amount of ash that is volatile and settles in ash collectors. It can cause abrasive damage to the pipes in the heat exchanger. It was proposed to install a flow meter in the ash collector pipes that deliver ash from the ash collectors to mix with the slurry. This helped to determine the correlation between the ash flow that potentially damages the pipes and the actual ash content of the fuel as a whole.

It was proposed to use the ultrasonic slurry flow meter DENCELL® UDF-2 to keep records of slurry flow. Typically, the objects where these flow meters are implemented are industrial and production facilities, mining enterprises, mining and processing plants, mines, open-pit mines, raw material extraction enterprises, etc.

To keep records of ash flow from ash collectors to mixing with the main slurry, it is proposed to use a flow meter, Siemens Solids flowmeter SITRANS® WF300 Series.

Thus, taking into account the transport delay and the density of the technical liquid in the slurry, it became possible to calculate the actual ash content of the fuel and how it affects the wear resistance of the heating surfaces of boiler equipment. Therefore, with the help of a small amount of additional equipment, the problem of determining the abrasiveness of fuel in the absence of a laboratory with free access was solved. The next step was to build a mathematical model to find out the discrepancy between the specified and actual indicators of the flow of abrasive material during the combustion of coal.

5. Development of a Mathematical Model for the Detection of the Inconsistency of Fuel Quality Indicators During its Combustion in the TPP Furnace

In [10], a parametric scheme was constructed to understand the TPP links, and these links were combined in the form of a system of equations. Now, it

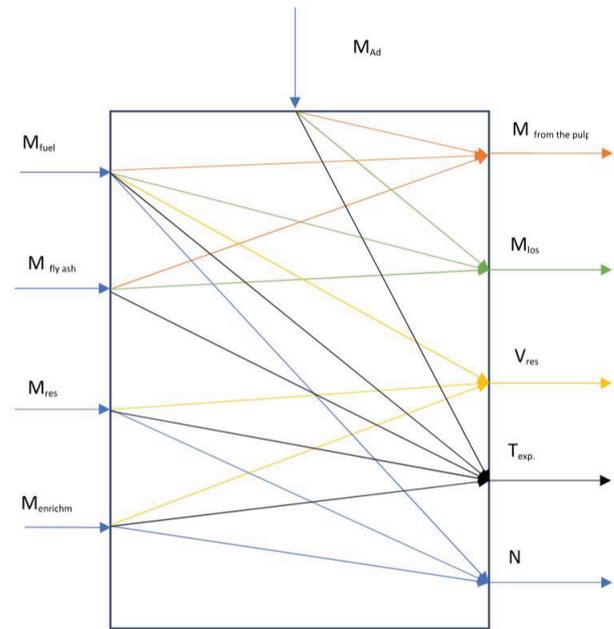


Figure 4. Parametric scheme of the boiler unit

was necessary to find the links with expressions in ash flows.

The connections between these parameters are described by a system of equations (3):

$$\begin{cases} M_{sl} = M_f a_1 + M_{f,a} a_2 + M_{Ad} a_3 \\ M_{loss} = M_f b_1 + M_{f,a} b_2 + M_{Ad} b_3 \\ V_{res} = M_f c_1 + M_{res} c_2 + M_{en} c_3 \\ T_{op} = M_f d_1 + M_{f,a} d_2 + M_{Ad} d_3 + M_{res} d_4 + M_{en} d_5 \\ N = M_f e_1 + M_{res} e_2 + M_{en} e_3 \end{cases}, \quad (3)$$

where a_n, b_n, c_n, d_n, e_n - constant coefficients; $n = 1, 3; m = 1, 5$

M_f - is the fuel consumption, kg/h;

M_{en} - is the enriched fuel consumption, kg/h;

M_{res} - is the reserve fuel consumption, kg/h;

$M_{f,a}$ - is the fly ash flow from ash collectors, kg/h;

M_{Ad} - is the ash content of fuel, %;

M_{sl} - is the flow of total ash and slag slurry, kg/h;

T_{op} - is the operating time before replacing the heat exchanger pipes, h;

M_{loss} - is the carbon losses due to the discrepancy between the declared and actual ash content, which is lacking, which makes it necessary to enrich or use reserves, kg/h;

V_{res} - is the fuel stock in the reserve warehouse, t;

N - is the plant capacity, MW.

To calculate the three main tasks: the volume of the fuel reserve, the flow of abrasive fly ash, and the operating time of the equipment at the current abrasive wear of pipes during fuel combustion, this system was written in another form.

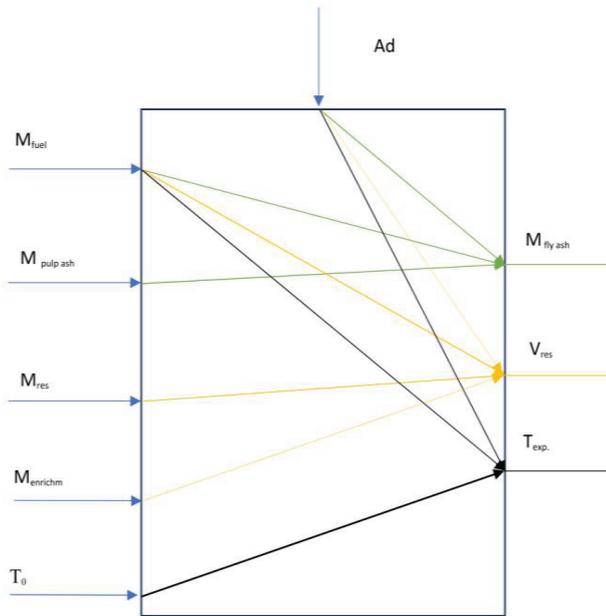


Figure 5. Parametric scheme of the boiler unit expressed in ash flows

The parametric scheme and the system of equations were presented in the following (4):

$$\begin{cases} M_{f,a} = M_{sl} - F_{f,a}(M_f, A_d) \\ V_{res} = V_0 - F_{en}(M_f, A_d, M_{en}) \\ T_{op} = T_0 - F_T(M_f, A_d) \end{cases} \quad (4)$$

The fuel combustion process in the input fuel and output emission streams is described (5), with the variable A_d as a function of time τ :

$$\begin{aligned} \frac{dM_{A_d}}{d\tau} &= (M_{ash} + dM_{ash}) - (M_{sl} + dM_{sl}) \\ M_{ash} - M_{sl} &= 0 \\ \frac{dM_{A_d}}{d\tau} &= dM_{ash} - dM_{sl}, \end{aligned} \quad (5)$$

where M_{ash} – is the general ash flow consumption.

Thus, the scheme was formulated, the regulator was proposed, and it became possible to control the flow of abrasive material.

6. Development of a Control Device Based on Fuzzy Logic to Control the Wear Resistance of the Heat Exchange Surface by Controlling the Quality of Coal by Distributing Coal Flows

The following scheme of regulation of the main flows of TPPs is proposed.

To synthesize the controller, we first considered the simulation model of the CICS for regulating the power unit power supply with coal fuel (Fig. 7), which was built using [8, 29]. The simulation was carried out using the interactive tool MATLAB®, Simulink® (LICENSING 110721904 – MathWorks Trial – 22 Oct 2022).

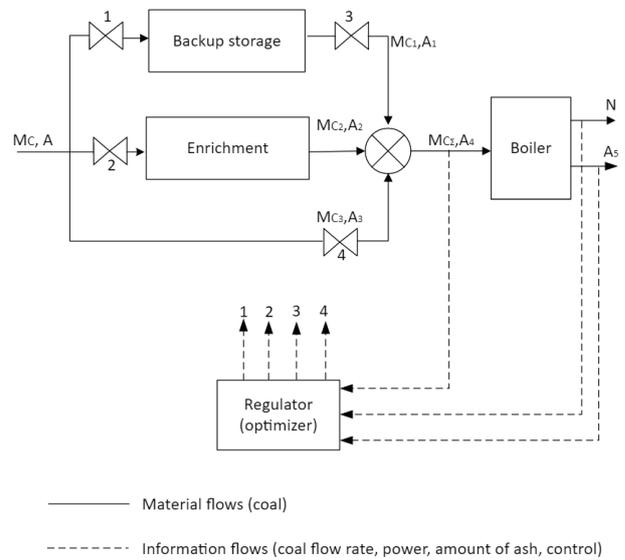


Figure 6. The scheme of regulation

The following notations are used in the figure: Concentrator-fuel enrichment system, Grand Controller-control system consisting of local regulators, and decision-making system for coal flow distribution.

To regulate the power unit load, it is sufficient to use a standard PID controller [30, 31].

In this work, attention is paid to the development of a control influence to comply with the specified abrasiveness characteristics of coal supplied for combustion.

In [6, 7], the issues of calculating the rates of abrasive damage to the pipe part of the boiler unit during fuel combustion are considered. The following formula (6) is given:

$$T = \frac{(\delta_w - \delta_{min.w})}{(3,6 \cdot \delta_{sp.h} \cdot G_M)}, \quad (6)$$

where T is the possible operating time of the equipment at the current level of abrasiveness; δ_w – pipeline wall thickness, mm; $\delta_{min.w}$ – standard minimum pipeline wall thickness, mm; $\delta_{sp.h}$ – specific linear abrasive wear of the pipeline, mm/t of abrasive in the fuel flow of the combusted material; G_M – mass flow rate of the material.

The sheet (Fig. 8) shows a comparison of the operating time at different coal abrasiveness values. The possibility of distributing the supplied coal flows in such a way as to regulate the abrasiveness of the mixture fed directly to the combustion was considered.

Taking into account the indicators of the operating time, the conditional coal classes and the controlling influence on the coal were formulated, i.e. decisions on combustion, enrichment, refusal of combustion, etc.

Given that the boundary values of the classes were taken as conditional (fuzzy) sets, the most appropriate was decided to use systems based on fuzzy logic.

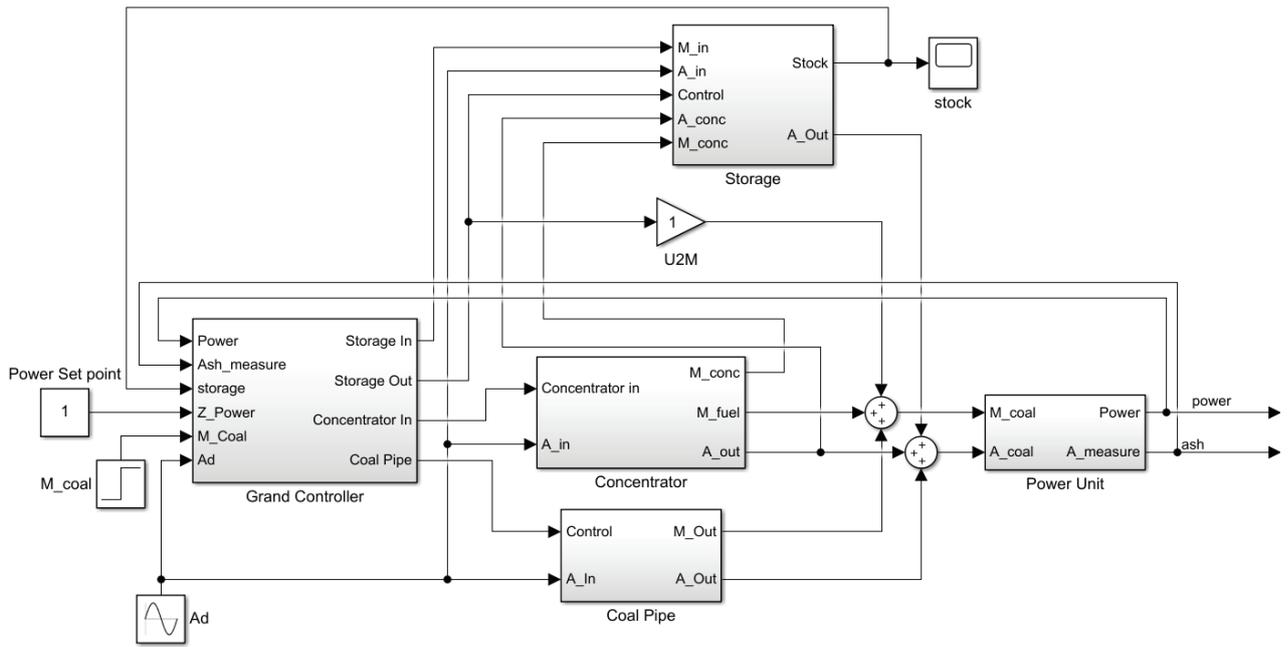


Figure 7. Simulation model of the regulatory system

n_{SiO_2}	fuel class	from, years	to, years	controlling influence
0-5%	Ideal	-	17,75	Send to the reserve warehouse.
5-9%	Good	17,69	9,43	Use for burning.
9-16%	Normal	9,42	4,89	Partially enrich or mix with the reserve.
16-30%	Unsatis-fied	4,89	2,17	To enrich, or to enrich and mix with a reserve.
30+%	Bad	2,17	-	Mix with the reserve, or use only the reserve.

Figure 8. Sheet of proposed coal classes with recommendations for fuel class

In [32-35], the control of processes based on fuzzy logic was investigated, from where three main advantages of using a fuzzy control device over traditional regulators of automatic control theory were emphasized:

- the possibility of combining adaptive type controllers based on classical PID controllers;
- development of complex controllers for control objects that are difficult to describe by analytical means; and
- a faster transition between control processes.

Using the material from [36-38], we will build a fuzzy control device.

As input information flows for the fuzzy controller, we take the ash content of the fuel (further A_{ds} in the controller's rules), the fullness of the reserve store, and the distribution of the fuel flow in the corresponding fractions in the following directions is taken as the control influence: to replenish the reserve store directly for combustion (burning), to enrichment (concentrator), and complete rejection of the current coal and the use of the reserve (reserve_out).

The condition problem of Figure 8.1. corresponds to the coal classes from Figure 8 and will influence the choice of fuel action, while Figure 8.2. will influence the replenishment and use of TPP reserve.

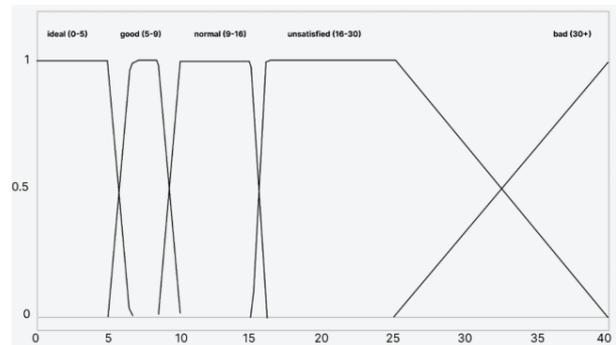


Figure 8.1. Variable fuzzification A_d

The rules of flow distribution were specified as follows (Fig. 9):

Where: St – flow of refill of the warehouse; Br – flow for fuel combustion; Cn – flow to the concentrator; Re – flow of the reserve fuel usage; and s/n/l mean small/ normal/large flow level.

Thus, the scheme of the control system (Grand Controller) Figure 10:

Rules are presented in Figure 11.

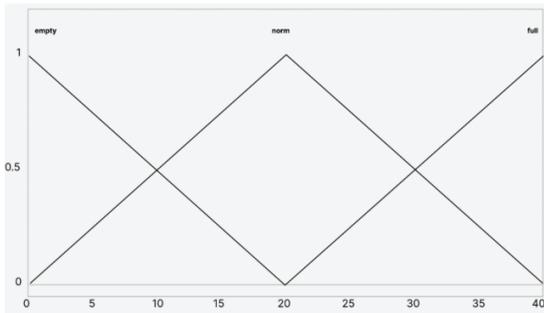


Figure 8.2. Variable fuzzification store

rule №	Ad, %	class of fuel	storage	St	Br	Cn	Re
1	0-5	ideal	full	s	l	s	s
2			norm	n	n	s	s
3			empty	l	n	s	s
4	5-9	good	full	s	l	s	s
5			norm	s	l	s	s
6			empty	n	n	s	s
7	9-16	norm	full	s	l	s	s
8			norm	s	l	s	s
9			empty	s	l	n	s
10	16-30	unsatisf	full	s	n	n	n
11			norm	s	n	n	n
12			empty	s	n	n	n
13	30+	bad	full	s	s	n	l
14			norm	s	s	n	l
15			empty	s	s	n	l

Figure 9. Rules table for a fuzzy controller

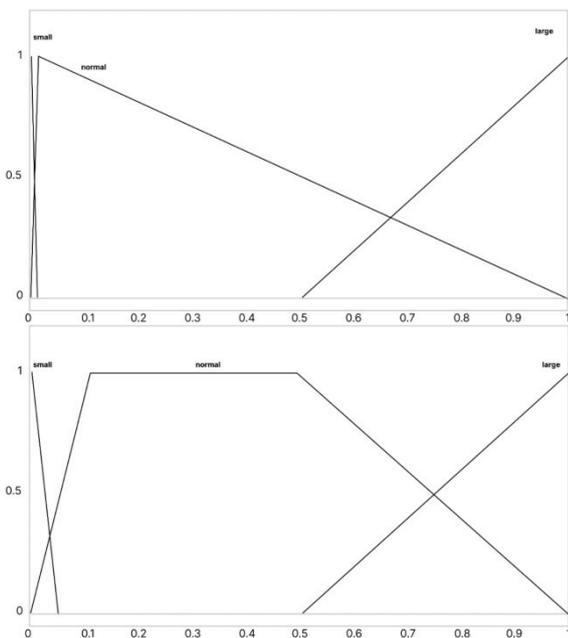


Figure 9.1. Defuzzification of control influences

7. Modelling the Influence of the Control Device at Different Indicators of Coal Abrasiveness

The constructed regulator works in such a way that it distributes in percentage fractions the directions of steam coal flow. It was also necessary to check how the regulator works at different indicators of abrasive material content in the fuel.

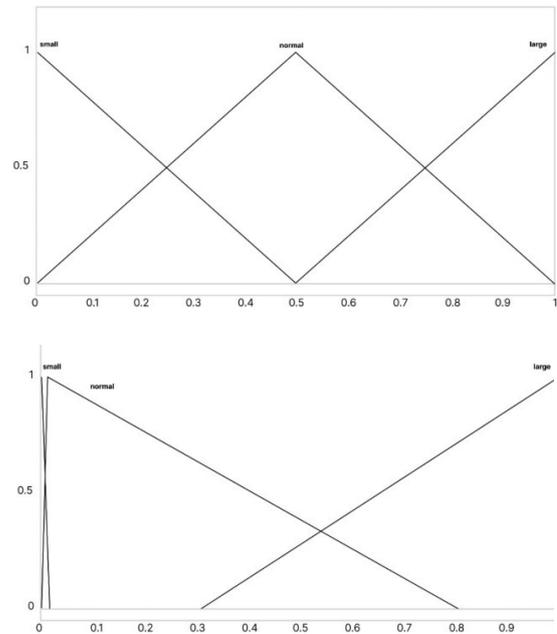


Figure 9.2. Defuzzification of control influences

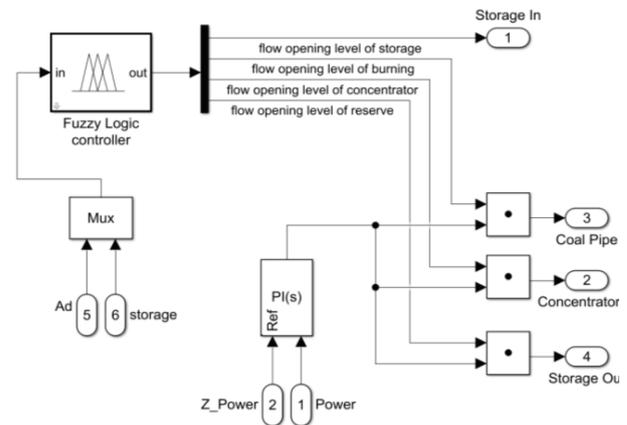


Figure 10. Scheme of the control unit (Grand Controller unit) Prepared by authors, using instructions from [30, 31, 38]

Modeling of the system showed that:

- If the coal is “Perfect”, when the reserve stock is not filled, is almost evenly distributed between the furnace and the reserve stock, because, due to the high carbon content and almost zero abrasive content, the combustion requirements are lower than for other classes of steam coal.
- If the coal is “Good”, with an almost full and almost empty stockpile, is distributed between the furnace and the stockpile for reserve replenishment in the appropriate proportions depending on the need for a reserve.
- In case of abrasiveness between “Normal” and “Unsatisfied”, the coal is divided between the furnace flow and the enrichment flow and partially mixed with the reserve coal.

At abrasiveness between “Unsatisfied” and “Bad” coal is sent for beneficiation and mixed with the reserve.

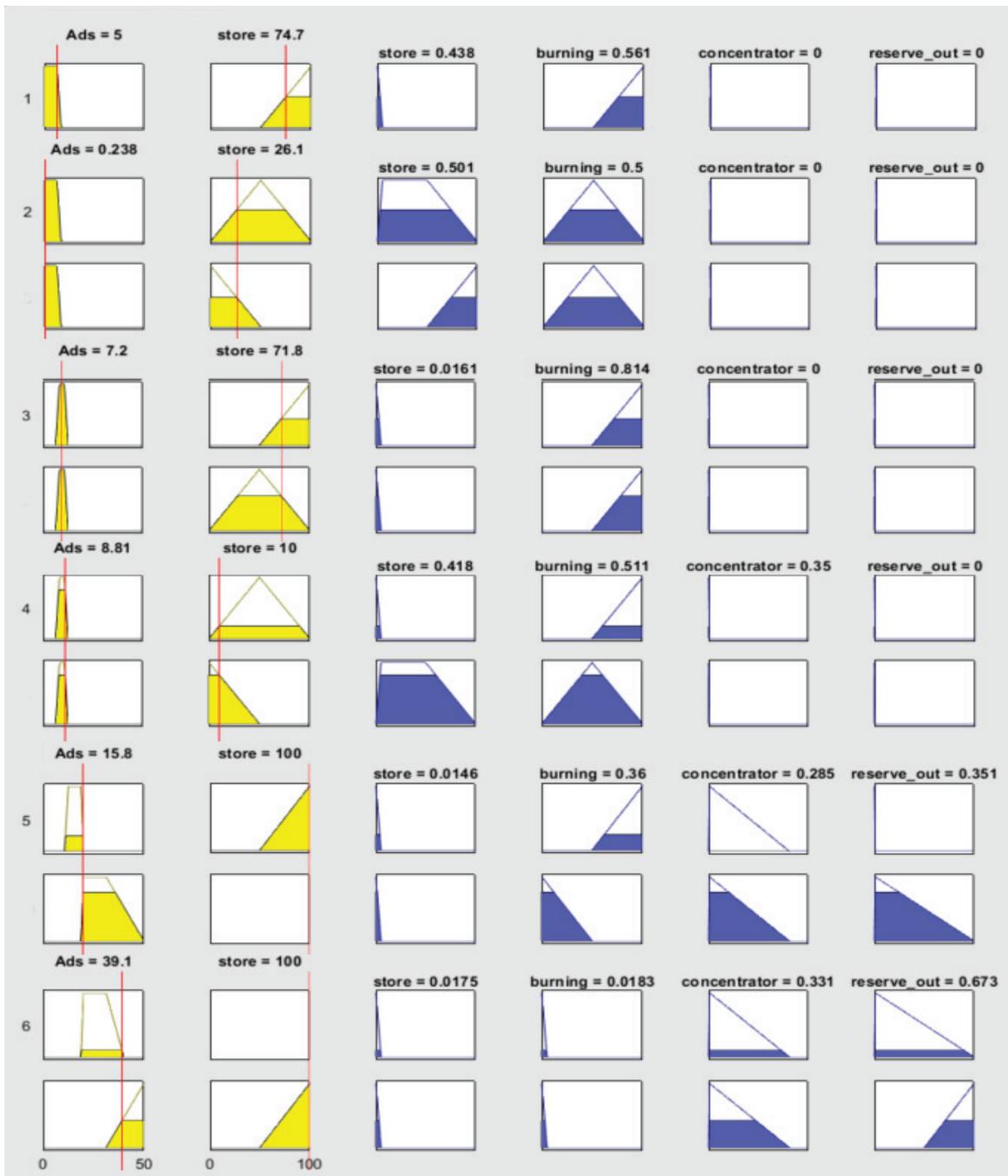


Figure 11. Checking the results of rules in Fig. 9 in rule viewer

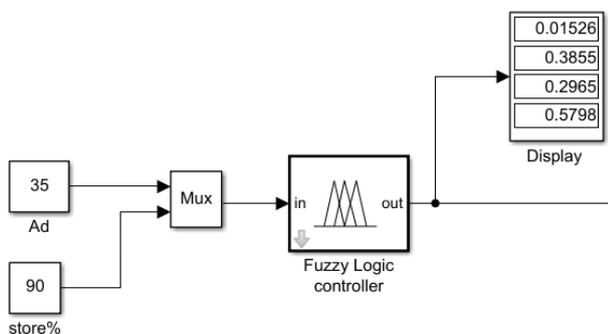


Figure 12. Scheme to test the results of coal flow control at a constant abrasiveness of 35% for 100-time units. Prepared by authors, using instructions from [29, 38]

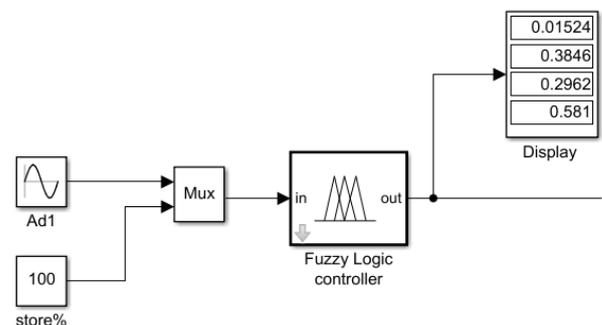


Figure 13.1. Schematic for checking the results of coal flow control when the abrasiveness index is steadily increasing for 100-time units. Prepared by authors, using instructions from [29, 38]

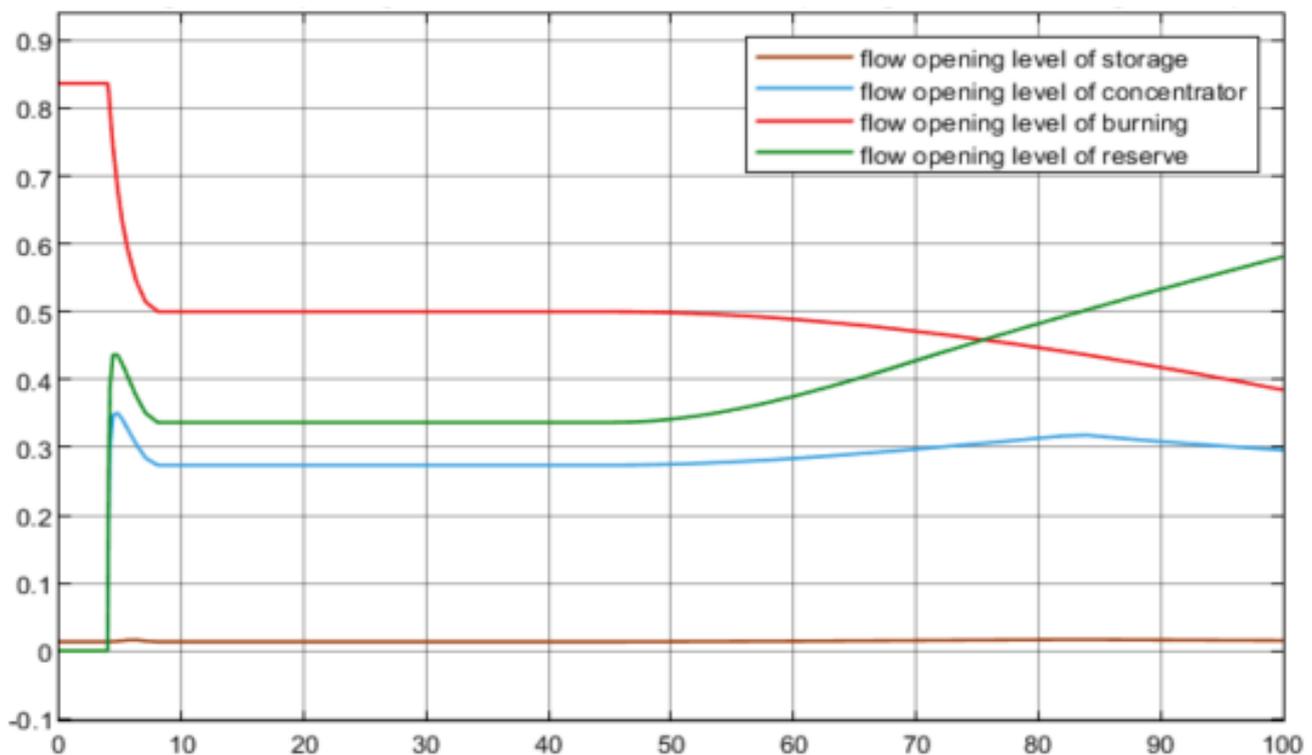


Figure 13.2. Chart of results for 13.1

At a constant $A_d = 35\%$, the graph shows that most of the coal fuel flow to the combustion furnace will come from the reserve, while the delivered coal will be distributed between the furnace and the beneficiation.

The case when A_d is constantly changing is considered. It continuously increases from 14% to 35% during 100-time units.

The results are shown in Figure 13.2 as follows:

- 1) At the initial $A_d = 14\%$ (system operating time $t_0 = 0$ s), almost the entire fuel flow is sent to combustion.
- 2) At the time of system operation $t_1 = 50$ s, the A_d will change and will be 24%. Therefore, the controlling influence will be the following distribution of fuel flows – half of the steam coal is sent for combustion, mixed with reserve fuel, and the rest is sent for enrichment.
- 3) At the end of the experiment ($t_2 = 100$) at $A_d = 35\%$, the largest share of the combusted fuel will be reserve energy coal, while the coal from the supplier will be partially burned and partially directed to enrichment.

With a fuel ash content of 35%, without a computer-integrated control system (CICS), TPP equipment can last approximately 632 days (less than 2 years) before breaking down. However, with an CICS, if the ash content is kept at the level of the Normal class, the equipment can last from 5 to 9 years.

With a steady increase in the content of abrasive material in steam coal, the consumption flow of the reserve is increased, and the consumption flow of the supplied ash fuel is reduced. This will help reduce the rate of erosion of the heat exchanger surface from the flow of abrasive material during combustion. Thus, it should be summarized that with the help of the proposed regulator, the set task has been solved.

8. Conclusion

This paper has investigated and developed a system for controlling the wear resistance of the heat exchange surface of a steam boiler of a coal-fired power plant by controlling the quality of the combusted fuel by the process of distributing steam coal flows with different abrasiveness content using fuzzy control.

The problem of measuring the current quality of coal was investigated by calculating and comparing the proposed equipment and modeled measuring channel of abrasive material content in steam coal for a CICS.

The next step was to develop a mathematical model to identify the inconsistency of fuel quality indicators during its combustion in the TPP furnace. The model was formulated in the form of a parametric scheme, taking into account the regulator, a system of equations, and the process of fuel combustion in the flows of input fuel and output emissions was recorded in the form of a differential equation, where the coal abrasiveness index was variable.

Subsequently, a control device based on fuzzy logic was developed. For the introduction of the fuzzy controller, a conditional division of coal quality into five

classes was proposed, and, accordingly, five control influences were proposed. The rules for the distribution of coal flows, which will guide the regulator of the CICS, were formulated and written down, and computer simulation was carried out to control the wear resistance of the heat exchange surface by controlling the quality of coal by distributing the flows of coal sent for combustion.

The developed control system has been validated by simulating the plant control to determine the optimal control action for different coal qualities. In addition, this CICS successfully reduces the harmful effects on the equipment.

The obtained results of computer simulation confirm the high efficiency of the use of fuel enrichment and the fuzzy CICS, which allows for the observation of the combustion of the required amount of coal to maintain the proper level of grid capacity but to reduce the harmful effects of wear resistance of the heat exchanger of the coal-fired power plant.

Further research should consider the logistical problem, in particular, the management of transport delay of steam coal supply under the condition of different fuel quality, as well as propose a method for controlling the system as a whole in combination with a fuzzy control system of TPP.

AUTHORS

Maksym Grishyn* – Department of Software and Computer-Integration Technologies, National University “Odesa Polytechnic”, 65000 Odesa, Ukraine, e-mail: grishyn.m.v@opu.ua.

Kostiantyn Beglov – Department of Software and Computer-Integration Technologies, National University “Odesa Polytechnic”, 65000 Odesa, Ukraine, e-mail: beglov.kv@op.edu.ua.

*Corresponding author

References

- [1] IEA, “World gross electricity production by source,” 2019; <https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2019>.
- [2] IEA, “Energy Statistics Data Browser,” 2022; <https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser>.
- [3] M.R. Kadagala, S. Nikkam, and S.K. Tripathy, “A Review On Flotation Of Coal Using Mixed Reagent Systems,” *Minerals Engineering*, vol. 173, 2021, 107217, ISSN 0892-6875, doi: 10.1016/j.mineng.2021.107217.
- [4] M. Polat, H. Polat, and S. Chander, “Physical And Chemical Interactions In Coal Flotation,” *International Journal of Mineral Processing*, vol. 72, no. 1–4, 2003, pp. 199–213, doi: 10.1016/S0301-7516(03)00099-1.
- [5] J. Ferrer-Comalat, S. Linares-Mustarós, J.M. Merigo, and J. Kacprzyk, “Modelling and Simulation in Management Sciences,” *Proceedings of the International Conference on Modelling and Simulation in Management Sciences (MS-18): Proceedings of the International Conference on Modelling and Simulation in Management Sciences (MS-18)*, 2020, doi: 10.1007/978-3-030-15413-4.
- [6] S.N. Pelykh and M.V. Maksimov, “The Method Of Fuel Rearrangement Control Considering Fuel Element Cladding Damage And Burnup”, *Problems of Atomic Science and Technology*, vol. 87, no. 5, 2013, pp. 84–90, <https://vant.kipt.kharkov.ua/TABFRAME.html>.
- [7] M.V. Maksimov, S.N. Pelykh, and R.L. Gontar, “Principles Of Controlling Fuel-Element Cladding Lifetime In Variable VVER-1000 Loading Regimes”, *Atomic Energy*, vol. 112, no. 4, 2012, pp. 241–249, doi: 10.1007/s10512-012-9552-3.
- [8] W. Wang, J. Liu, Z. Gan, Y. Niu, and D. Zeng, “Flexible Control Of Combined Heat And Power Units Based On Heat-Power Estimation And Coordination”, *International Journal of Electrical Power & Energy Systems*, vol. 123, 2020, 106261, ISSN 0142-0615, doi: 10.1016/j.ijepes.2020.106261.
- [9] W. Tan, J. Liu, F. Fang, Y. Chen, “Tuning of PID Controllers For Boiler-Turbine Units”, *ISA Transactions*, vol. 43, no. 4, 2004, pp. 571–583, ISSN 0019-0578, doi: 10.1016/S0019-0578(07)60169-4.
- [10] M.V. Grishyn and K.V. Beglov, “Evaluating The Effectiveness Of Fuel Enrichment To Reduce The Risk Of Power Plant Costs,” *Včeni zapiski Tavrijs’kogo nacional’nogo universitetu imeni V. Ī. Vernads’kogo. Seriâ Tehnični nauki*, vol. 32, no. 3, 2021, pp. 82–89, doi: 10.32838/2663-5941/2021.3/14.
- [11] Z. Dong, R. Wang, M. Fan, and X. Fu, “Switching And Optimizing Control For Coal Flotation Process Based On A Hybrid Model,” *PLoS ONE*, vol. 12, no. 10, 2017, e0186553, doi: 10.1371/journal.pone.0186553.
- [12] Q. Tian, H. Wang, and Y. Pan, “Associations of Gangue Minerals in Coal Flotation Tailing and Their Transportation Behaviors in the Flotation Process,” *ACS Omega*, vol. 7, no. 31, 2022, pp. 27542–27549, doi: 10.1021/acsomega.2c02988.
- [13] A.I. Brunetkin and M.V. Maksimov, “The Method For Determination Of A Combustible Gase Composition During Its Combustion,” *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 5, 2015, pp. 83–90, <http://nvngu.in.ua/index.php/uk/arkhiv-zhurnal/za-vipuskami/1132-2015/zmist-5-2015/tekhnologiji-energozabezpechennya/3162-metod-viznachennya-skladu-goryuchikh-gaziv-pri-jikh-spalyuvanni>.

- [14] Y.V. Shcheglov, N.V. Fedorova, and D.A. Shaforost, "The Abrasive Properties of Coal Power Plants Ash and Slag Materials," *Solid State Phenomena*, vol. 299, 2020, pp. 845–851, doi: 10.4028/www.scientific.net/SSP.299.845.
- [15] I. Kocaarslan, E. Çam, and H. Tiryaki, "A Fuzzy Logic Controller Application For Thermal Power Plants," *Energy Conversion and Management*, vol. 47, 2006, pp. 442–458. doi: 10.1016/j.enconman.2005.05.010.
- [16] A.Z. Cipriano, "Fuzzy Predictive Control for Power Plants," *Advanced Fuzzy Logic Technologies in Industrial Applications, Advances in Industrial Control*, 2006, pp. 279–297, doi: 10.1007/978-1-84628-469-4_19.
- [17] Y.P. Kondratenko and A.V. Kozlov, "Generation of Rule Bases of Fuzzy Systems Based on Modified Ant Colony Algorithms," *Journal of Automation and Information Sciences*, vol. 51, no. 3, 2019, pp. 4–25, doi: 10.1615/JAutomatInfSci.v51.i3.20.
- [18] O. Kozlov, Y. Kondratenko, H. Lysiuk, V. Kryvda, and O. Maksymova, "Fuzzy Automatic Control of the Pyrolysis Process for the Municipal Solid Waste of Variable Composition," *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 16, no. 1, 2022, pp. 83–94, doi: 10.14313/JAMRIS/1-2022/9.
- [19] S. Satyanarayana, R.K. Sharma, Mukta and A.K. Sappa, "Automatic Generation Control In Power Plant Using PID, PSS And Fuzzy-PID Controller," *2014 International Conference on Smart Electric Grid (ISEG), Guntur, India, 2014*, pp. 1–8, doi: 10.1109/ISEG.2014.7005618.
- [20] O. Kozlov, G. Kondratenko, Z. Gomolka, and Y. Kondratenko, "Synthesis and Optimization of Green Fuzzy Controllers for the Reactors of the Specialized Pyrolysis Plants," *Green IT Engineering: Social, Business and Industrial Applications, Studies in Systems, Decision and Control*, V. Kharchenko, Y. Kondratenko, and J. Kacprzyk, eds., Springer, Cham, 2019, pp. 373–396, doi: 10.1007/978-3-030-00253-4_16.
- [21] Y.P. Kondratenko and A.V. Kozlov, "Parametric Optimization Of Fuzzy Control Systems Based On Hybrid Particle Swarm Algorithms With Elite Strategy," *Journal of Automation and Information Sciences*, vol. 51, no. 12, 2019, pp. 25–45.
- [22] Q. Bu et al. "The Effect Of Fuzzy PID Temperature Control On Thermal Behavior Analysis And Kinetics Study Of Biomass Microwave Pyrolysis," *Journal of Analytical and Applied Pyrolysis*, vol. 158, 2021, 105176, doi: 10.1016/j.jaap.2021.105176
- [23] X. Liu, S. Wang, and L. Xing, "Fuzzy Self-Tuning PID Temperature Control For Biomass Pyrolysis Fluidized Bed Combustor," *2010 2nd IEEE International Conference on Information Management and Engineering*, 2010, pp. 384–387, doi: 10.1109/ICIME.2010.5477837.
- [24] M. Ovcharenko, "DTEK investuie 117 mln hrn na ekolohichnu modernizatsiiu Prydniprovs'koi TES," *uprom.info*; <https://uprom.info/news/energy/dtek-investuye-117-mln-grn-na-ekologic-hnu-modernizatsiyu-pridniprovskoyi-tes/> (in Ukrainian).
- [25] G.L. Fisher, D.P.Y. Chang, and M. Brummer, "Fly Ash Collected from Electrostatic Precipitators: Microcrystal- lines Structures and the Mystery of the Spheres," *Science*, vol. 192, no. 4239, 1976, pp. 553–555, doi: 10.1126/science.192.4239.553.
- [26] Guarantees Of Citizens' Environmental Rights, Document 1264-XI, Article 10, Law Of Ukraine On Environmental Protection; <https://zakon.rada.gov.ua/laws/main/1264-12?lang=en#Text>.
- [27] V.G. Vasilenko, "Methodical Recommendations for Evaluation of Greenhouse Gas Emissions by Type of Activity of Facilities, Annex to the Order of the Ministry of Environmental Protection and Natural Resources of Ukraine on Approval of Methodical Recommendations for Evaluation of Greenhouse Gas Emissions by Type of Activity of Facilities №404," 2021, <https://mepr.gov.ua/files/docs/nakazy/2021/404%D0%BD%D0%B41.pdf> (in Ukrainian).
- [28] D.V. Chugunkov, G.A. Seyfelmiukova, V.P. Kuzema, and A.E. Bogdanova, "Research on structure of ash-slag pulp and its influence on pipelines' attrition of a thermal power plants' hydraulic ash removal system," *Journal of Physics: Conference Series*, vol. 1370, no. 1, 2019, doi: 10.1088/1742-6596/1370/1/012015.
- [29] L.A. Kumar, A. Kalaiarasi, and Y.U. Maheswari, *Power Electronics with MATLAB*, Cambridge University Press, 2017.
- [30] L. Wang, S. Chai, D. Yoo, L. Gan, and K. Ng, "PID and Predictive Control of Electrical Drives and Power Converters using MATLAB/Simulink," *IEEE Press*, 2015.
- [31] L. Wang, "PID Control System Design and Automatic Tuning using MATLAB/Simulink: Design and Implementation using MATLAB/Simulink," *IEEE Press*, 2020.
- [32] M. Jamshidi, V. Kreinovich, and J. Kacprzyk, *Advance Trends In Soft Computing*, Springer, 2013. doi: 10.1007/978-3-319-03674-8.
- [33] J. Kacprzyk, *Multistage Fuzzy Control: A Prescriptive Approach*, John Wiley & Sons Inc., 1997.
- [34] E. Szmidt and J. Kacprzyk, "Distances between intuitionistic fuzzy sets," *Fuzzy Sets and Systems*, vol. 114, no. 3, 2000, pp. 505–518, doi: 10.1016/S0165-0114(98)00244-9.
- [35] E. Szmidt and J. Kacprzyk. "A Consensus-Reaching Process Under Intuitionistic Fuzzy

- Preference Relations”, *International Journal of Intelligent System*, vol. 18, 2003, pp. 837–852, doi: 10.1002/int.10119.
- [36] W. Pedrycz, K. Li, and M. Reformat, “Evolutionary Reduction Of Fuzzy Rule-Based Models,” *Fifty Years of Fuzzy Logic and its Applications*, Springer, 2015, pp. 459–481, doi: 10.1007/978-3-319-19683-1_23.
- [37] J. Jantzen, *Foundations of Fuzzy Control: A Practical Approach*, 2nd ed., John Wiley & Sons Inc, 2013, doi: 10.1002/9781118535608.
- [38] S.N. Sivanandam, S. Sumathi, and S. N. Deepa, *Introduction to Fuzzy Logic using MATLAB*, Springer International Publishing, 2007, doi: 10.1007/978-3-540-35781-0.