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Roman Karpenko,
Yevhenii Bondarenko

CONTROL OF BOILER EQUIPMENTS DURING STARTING AND STOPPING PERIODS AND METHODS OF OPTIMIZING THESE PROCESSES THROUGH THE USE OF A DECISION SUPPORT SYSTEM WITH A MACHINE VISION SUBSYSTEM

The object of research is the automation of starting and stopping steam power boilers. The problem of automating the starting and stopping of steam power boilers is important for thermal power plants (TPP) and industrial enterprises. These processes require significant efforts from service personnel due to their complexity, partial automation and the need to take into account the human factor. It is emphasized that full automation of starting and stopping steam boilers is economically impractical, since most of the time the boilers operate in continuous automatic operations and only a short time is allocated for periodic procedures, which are mostly performed manually. However, the significant impact of the human factor at critical stages of boiler operation requires the introduction of new technologies that can increase the efficiency and safety of such operations. The study outlines the main challenges associated with steam boiler control and proposes new approaches to solving these problems. It is noted that operators often perform actions during boiler starting and stopping based on instructions or their own experience. This knowledge can be formalized and integrated into the database of an expert decision support system (DSS), which automates some of the manual actions and helps operators avoid errors. For this purpose, it is proposed to use machine vision subsystems that can validate the operator's actions, analyze the interaction of personnel with the equipment and signal about possible incorrect actions. This approach can not only reduce the risk of errors due to fatigue or stress of personnel, but also make the starting and stopping processes safer and more efficient.

It is proposed to integrate machine vision subsystems to obtain information that is difficult to measure by traditional means, in particular, regarding the operator's interaction with manual mechanisms or its presence at the workplace. The structure of the proposed DSS also takes into account the possibility of transferring knowledge bases between different objects, which ensures the scalability and adaptability of the system. The implementation of such a system is based on modern international automation standards, in particular ISA-88, ISA-106 and VDI/VDE/VDMA 2632.

Keywords: *decision support system, machine vision, steam boiler, production equipment, control procedures, manual equipment.*

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1. Introduction

Starting and stopping a power steam boiler is usually a laborious task and requires highly qualified service personnel. However, according to statistics, the automation system of this type of installation operating at thermal power plants (TPPs) and power plants does not provide a full degree of automation of all processes without the intervention of service personnel. From an economic point of view, full automation is not entirely advisable, because the operation of a steam boiler is a continuous process, where 90 % of the time is spent on continuous automatic operations, and only 5–10 % of the total time is spent on stops and starts. Therefore, part of the actions during such periodic operations as starting and stopping a steam boiler is usually accompanied by a number of manual actions performed by the operator. The operator acts using job instructions, and as is often the case, based on its own experience gained in the process of work. This knowledge can be collected and compiled into an expert database, which can later be used to build a decision support system and automate the execution of such periodic operations. And the machine vision subsystem will allow validating the actions of operators during their interaction with technological equipment. This approach will allow

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optimizing actions during emergency situations and starting and stopping processes, as well as reducing the impact of the human factor on the course of these processes, which will make them safer and more efficient.

During the preparation of the materials, the works of scientists in the field of nuclear energy and in the field of electricity generation in general were analyzed [1–5]. Thus, in work [1] the construction of a machine vision system for analyzing the condition of manual valves at nuclear power plants is described. The stages of building such a system is described. The results of laboratory research are presented and the strengths and weaknesses of using such systems are described. The implementation of their system can be supplemented with additional analysis of indicating devices installed near pipeline valves, since they can also indirectly indicate the position of manual valves. In [2], the implementation of a prototype of a decision support system is shown, which is used to assist operational personnel at a nuclear power plant. The system interface is implemented as a separate window of the human-machine interface. The system contains a base of rules according to which the operator must act, and a base of conditions according to which these rules must be implemented. That is, these are pre-written procedures for human-system interaction. There is also validation of operator actions. If the operator performs an incorrect action on a certain condition, the system warns about this with an alarm. This decision support system (DSS) can be supplemented by using a machine vision system to validate the operator's actions, that is, using cameras to analyze whether the operator interacts with the necessary equipment manually, or presents at the workplace at all. It is also possible to track the route of its movement in emergency situations, for its safety and to increase efficiency. In [4], it is described how the operator interacts with various parts of the control system and other personnel in the process of servicing an industrial facility. Thus, the authors divide the human impact on the functioning of an industrial facility into several parts: physical human reliability (well-being, cognitive functions), team reliability (interaction with other personnel), cyber reliability (correctness of the operator's actions during the operation of the equipment). All these aspects affect the safety of the operator itself and the activities of the industrial facility as a whole.

Therefore, *the aim of research* is to develop a decision support system with a machine vision subsystem to optimize the control of boiler plants during their starting, stopping and in emergency situations. As well as with the ability to monitor the interaction of operational personnel with technological equipment, signaling about possible incorrect actions, collecting data during such events, and supplementing the expert database to adjust the DSS operation.

2. Materials and Methods

The research is based on modern scientific materials that study the management of industrial energy facilities, the influence of the human factor on the functioning of such facilities, and methods for optimizing the management of such facilities. Practical engineering methods for controlling continuous processes and periodic operations in production, methods for developing and implementing machine vision systems are used as methodological support. The work uses industry technical standards ISA-88/IEC-61512 and ISA-106, the VDI/VDE/VDMA 2632 series of standards.

3. Results and Discussion

3.1. Problems of performing typical procedures during boiler operation

Steam power boilers can be divided into several groups, distinguishing them by type of fuel: solid fuel, liquid fuel, and gas [6]. Solid fuel, in turn, can be: coal, biomass, and waste incineration. This division into types of fuel is due to the structure of the boiler, and as a result, a different number of mechanisms in the control system, both manual and remote-controlled. At the same time, for all types of boilers there are a number of typical operations that are performed by service personnel in different operating modes. These include:

- fuel loading (in the case of solid fuel boilers);
- combustion control;
- cleaning heating surfaces from scale or ash;
- regulation of thermal modes;
- inspection and maintenance of water supply systems;
- safety monitoring and troubleshooting.

Such operations ensure stable operation of the boiler, efficient use of fuel and minimizing environmental impact.

In the event of abnormal or emergency situations, the operator performs actions in accordance with safety regulations. The main measures are:

- immediate reduction of steam pressure by discharging into the atmosphere or a backup consumption system;
- stopping the supply of fuel and air for combustion;
- switching the system to emergency cooling mode;
- switching on the emergency water supply to protect the boiler from overheating.

In addition, the operator is obliged to assess the cause of the accident using diagnostic systems, notify the responsible persons and, if necessary, organize the evacuation of personnel. All actions must be clear and prompt in order to minimize risks to equipment, personnel and the environment.

Preparation for the ignition of a steam power boiler includes a thorough check of all systems and mechanisms to ensure safe starting. First, the condition of the firebox is checked, cleaning from ash residues or ash, as well as the correct location of fuel materials (for solid fuel boilers). Next, the water level in the boiler drum is monitored, the water temperature complies with the regulatory values, and the serviceability of the water treatment system is checked. The operator checks the operability of the fuel and air supply systems, the tightness of pipelines and fittings. The control system is put into preparation mode, automatic control systems are activated, after which the fuel and air supply for combustion initiation is gradually started. During the ignition process, the operator monitors the stability of the flame, uniform heating of the water and a gradual increase in steam pressure.

The boiler is stopped in the reverse sequence in order to safely complete its operation. The fuel supply is gradually reduced until it stops completely, and at the same time the air supply intensity is reduced. The operator ensures a gradual decrease in steam pressure by controlling its use or discharge. After this, the furnace and heat exchange surfaces are cooled by circulating residual water or turning on cooling systems, if provided for by the design. Residual water is drained, the furnace and heat exchangers are cleaned of combustion products, and the condition of the equipment is checked to identify possible malfunctions before the next starting.

After the described actions, employees of thermal power plants who work for a long time under heavy load demonstrate reduced reliability in performing their duties due to physical fatigue, emotional exhaustion and cognitive overload. In such conditions, their actions become less accurate, the risk of making erroneous decisions increases, especially when performing complex or monotonous tasks. Constant stress and strain can lead to loss of concentration, slowed reactions, and a reduced ability to perceive and analyze information effectively. It is also likely that attention to small but critical details, for example, when working with control and measuring instruments or shut-off valves, will decrease. In an emergency situation, such workers may act impulsively or too slowly, which increases the risks to the safety of both the worker and the operation of the plant as a whole.

3.2. System structure

DSS can help in performing such typical procedures. This emphasizes the importance of implementing decision support systems to reduce the cognitive load on workers. The proposed approaches in the above studies offer DSS, which in thermal power plants usually do not fully cover the entire boiler automation system, leaving aside manual actuators that are still used for control and monitoring. This creates certain limitations, since information about the state of these mechanisms often remains outside the area of automated monitoring, which complicates a comprehensive assessment of the boiler's operation. In addition, the knowledge bases of such systems are difficult to transfer between the systems themselves, since their technical support in most cases differs significantly. Therefore, the work proposes:

1) to use machine vision in DSS to obtain information from the facility that is not measurable by traditional means;

2) to develop a structure and approaches that take into account the possibility of implementing a system with the ability to transfer the base between different facilities.

The implementation of a machine vision system allows monitoring the status of manual actuators in real time. Thanks to this, it is possible to obtain a more complete picture of the operating status of all system components, including those elements that are not integrated into automated systems. This, in turn, allows for prompt detection of malfunctions, increases operational safety and provides more accurate process control, which provides the operator with more information for making informed decisions. For a decision support system, such a machine vision system can be perceived as an intelligent sensor that analyzes the state of the equipment with which the operator can interact and draw a conclusion about the current state of the mechanism (open, closed, turned on, etc.). In turn, the DSS can perceive this information to form advice or actions regarding pre-written rules. The structural diagram of the interaction of such systems is shown in Fig. 1.

3.3. Stages of creating a decision-making and support system

1. Analysis of requirements and definition of system goals:

1.1. At the initial stage, it is necessary to determine the goals of the system. This may be optimization of boiler plant operation, increased safety, fuel economy or reduction of emissions.

1.2. It is necessary to analyze the necessary system functions, such as: monitoring the boiler condition, warning about emergency situations, or assistance in choosing the optimal operating mode parameters.

2. Designing the system architecture:

2.1. Development of the system structure, which includes a database, user interfaces, decision-making algorithms and the necessary subsystems for data collection and processing.

2.2. Determination of the types of sensors, gauges and other devices required to obtain information from boiler plants (temperature, pressure, water level, fuel consumption, etc.).

3. Modeling and selection of decision support algorithms:

3.1. Development of boiler operation models that will be used to assess the condition of boiler plants and predict their behavior.

3.2. Selection of decision support methods, such as expert systems, neural networks or optimization algorithms, that allow analyzing large amounts of data and offering the most effective solutions.

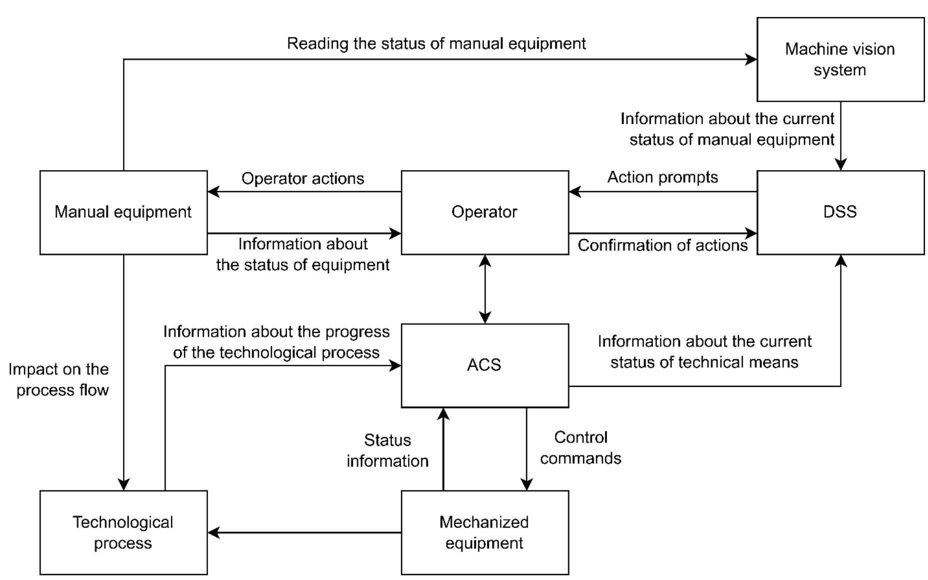

Fig. 1. Structural diagram of the interaction of the automated process control system (APCS) with the decision support system (DSS) and the machine vision subsystem

4. User interface development:

4.1. Creation of a user-friendly interface that allows boiler plant operators to interact with the system, receive recommendations or warnings.

4.2. The interface should be intuitive and adapted to specific user needs (for example, automatic parameter adjustment or issuing recommendations for optimizing boiler operation).

5. Integration with existing systems:

5.1. Integration of the DSS with other subsystems of the boiler plant APCS to ensure data exchange (for example, a system for monitoring operating parameters, emergency management, etc.).

5.2. Ensuring compatibility with different platforms and protocols to ensure uninterrupted operation.

6. System testing and validation:

6.1. Conducting tests to verify the correct operation of algorithms and interfaces, the correctness of data processing and the implementation of recommendations.

6.2. Validation of the system on real objects (boiler rooms) to verify its efficiency and reliability.

3.4. Implementation of the decision support system

1. Infrastructure deployment:

1.1. Installation of the necessary hardware components (servers, sensors, control panels) and their connection to the main DSS platform.

1.2. Setting up the network infrastructure to ensure data exchange between different components of the system.

2. Software configuration:

2.1. Installation of software that implements decision support algorithms, database, interaction interfaces and monitoring system.

2.2. Setting up the software for automatic data collection and launch of the necessary decision support algorithms.

3. Personnel training:

3.1. Conducting training for boiler plant operators on the use of the new system, explaining the functions, interfaces and decision-making processes.

3.2. Training personnel on working with new recommendations and algorithms, providing feedback for system improvement.

4. Using the system in real conditions:

4.1. After tuning and testing, the system is put into operation, where it begins to work in real boiler houses.

4.2. Operators use the system to monitor the condition of boilers and make decisions regarding their operation, energy conservation and accident risk reduction.

5. Support and improvement:

5.1. Regular software updates to improve decision-making algorithms or adapt to new operating conditions.

5.2. System support to eliminate possible failures or errors, as well as to add new functions or integrations.

Functional structure of the DSS. Based on the task, the proposed DSS should have the following operational functions:

a) determine the state of the object and system based on measurement information, including from the machine vision system, as well as information specified by the operator;

b) signal the operator about the need to starting procedures based on the formed rules and the specified state;

c) help the operator perform actions and monitor the procedure.

Based on the above operational functions shown in Fig. 2, the data processor must contain the following state determination submodules, which are designed to receive and process data from the system, on the basis of which the state of the object and the system as a whole is determined. It provides for the connection of both measurement data from the APCS system and from the machine vision system.

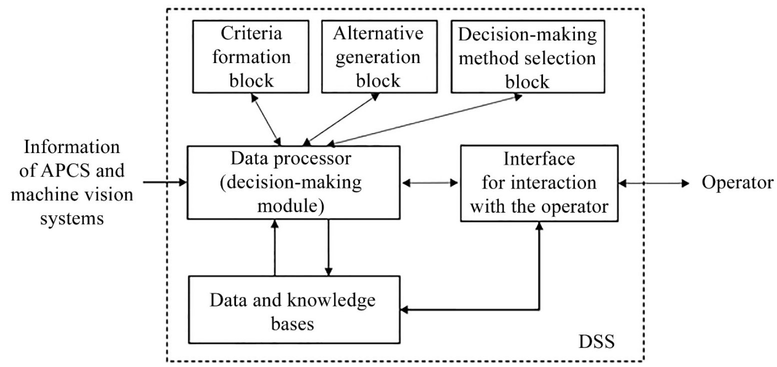

Fig. 2. Functional diagram of the decision support system

In the absence of some measured values of specific parameters of the power boiler (due to the complexity of the measurement or the high cost of hardware), it is possible to use data from the machine vision subsystem. This subsystem can output an approximate value of the position of manual actuators, which can then be interpreted in the format of linguistic variable values (for example: "very little", "little", "average", "a lot", "very much"). These linguistic variable values are used by the fuzzy set apparatus in the decision support system.

3.5. Equipment and states

It is proposed to introduce an explicit change in the state of the object, which will allow combining all sets of states into a smaller set, which will simplify both system maintenance and its operation. In addition to the states themselves, it is necessary to determine the entities to which they belong [7]. For this, it is recommended to use the existing ISA-106 standard [8]. According to the physical model of the equipment of this standard, our object of study (boiler) is at the level of technological nodes (Fig. 3). But it is also necessary to focus on the lower levels of this hierarchy: equipment and devices. Based on a certain set of device states, it is possible to judge a certain state of the equipment, and already by its state it is possible to determine the state and operating mode of our technological node, i. e. the boiler.

In the context of equipment management according to the ISA-106 standard, the key elements are the states of the equipment and their relationship with the procedures being performed. The state of the equipment determines its current position or operating mode, and the change of states is the basis for performing tasks. The standard offers various techniques for state management, among which special terms are defined:

1. *State* is a predefined position or operating mode of the equipment. For example:

1.1. For a shut-off valve: "open" or "closed".

1.2. For a PID controller: "manual mode", "automatic mode", "cascade mode".

1.3. For a pump: "started" or "stopped".

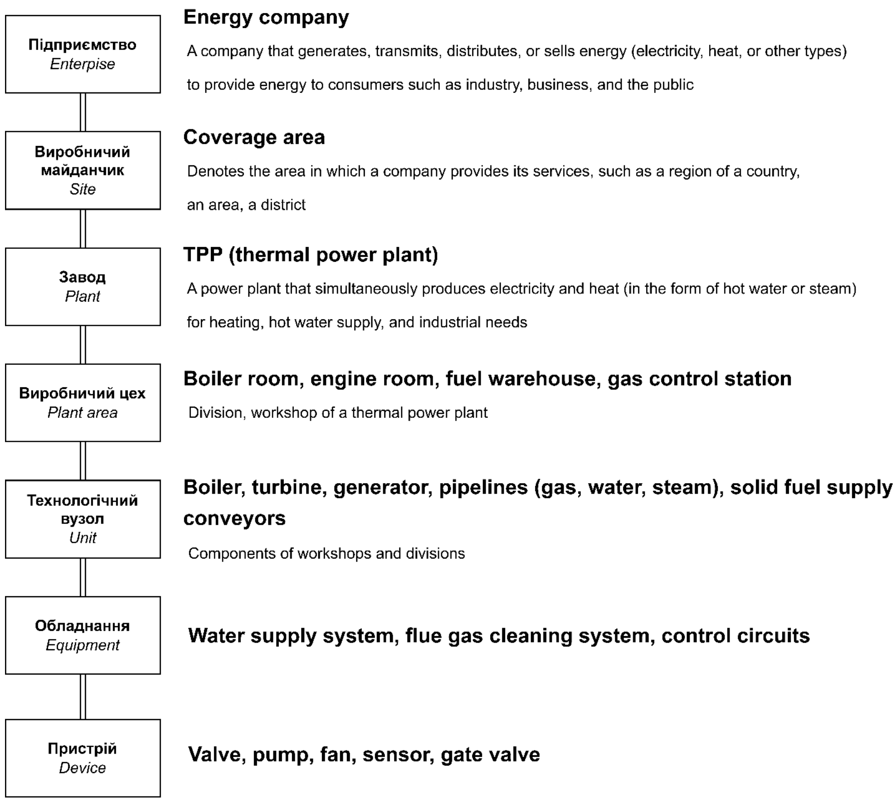

Fig. 3. Physical model of the role assignment of TPP equipment according to ISA-106

2. *Step* is a set of actions that the equipment performs according to its state. For example:

2.1. For a valve: "open to a given position".

2.2. For the pump: "smooth starting to operating speed".

2.3. For the regulator: "switching from manual mode to automatic with specified parameters".

Equipment state management is a sequential process that ensures the execution of tasks according to specified rules. For each state, corresponding inputs and outputs are set, which allows to clearly control the behavior of the equipment during the execution of procedures. This ensures reliability, predictability and consistency in the operation of the automation system. Table 1 shows a fragment of the list of equipment defined for the boiler unit and its states.

Table 1

A fragment of the list of possible equipment states

Equipment	Device	States
Water supply subsystem	–	Normal/Abnormal
–	Feed pump	Run/Stopped
–	Water shut-off valve	Open/Closed
–	Regulating valve	Position 0–100 %
–	PID regulator	Manual/Automatic
Gas supply subsystem	–	Normal/Abnormal
–	Gas shut-off valve	Open/Closed
–	Gas off valve	Open/Closed
–	Gas regulating valve	Position 0–100 %
–	PID regulator	Manual/Automatic

3.6. Use of machine vision

According to the proposed approach to state determination, each piece of equipment has a finite set of states. For manual equipment, the state is determined using machine vision. The method for determining the state was presented in [9]. Fig. 4 shows the functional diagram of the machine vision subsystem as part of the DSS.

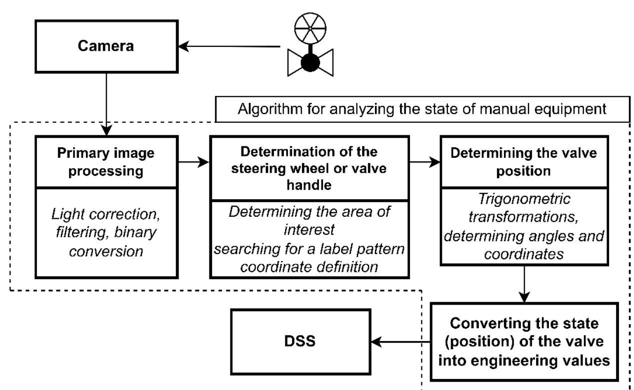

Fig. 4. Functional diagram of the machine vision subsystem as DSS part

The image from the camera installed near the manual valves undergoes initial processing, a special label and its position relative to the coordinate plane are determined on it. Then it is possible to convert this data into an engineering value and transfer it to the enterprise's information network for integration into various control systems, and as in our case, integrate it for interaction with the decision support system. Thus, it is possible to determine the states of manual valves that accept the open/closed states, as well as the position of multi-turn valves with a handwheel.

3.7. Formation of criteria for determining the state

The state or operating mode of the boiler can be determined by the value of the parameters that we control in it, or by the state of the equipment that is involved in the control. The set of a certain set of this information allows to determine the state in which the boiler is currently located. The power steam boiler can be in the following basic states:

1. Stopped.
2. Emergency stop.
3. Hot normal stop.
4. Full normal stop.
5. Ignition.
6. Warm-up.
7. Operation.

The boiler can transition to the above states either manually, by operator command, or automatically, according to certain rules. Below is a diagram of the boiler states and a description of the transition between them (Fig. 5). The dotted line on the diagram indicates transitions to temporary states, from which it is immediately possible to return to the final ones, without intermediate ones.

"Stopped" state. The boiler is in this state if: the smoke exhauster and fan are turned off, the fuel supply is blocked, there is no steam consumption, the pressure in the drum is below the operating limit, the combustion process is stopped, the temperatures in the furnace have dropped to the permissible ones (the boiler is cooled down). The boiler can enter the "stopped" state from the "full normal stop", "emergency stop" and "ignition" states. From the "stopped" state, the boiler can enter the "ignition" state.

"Ignition" state. The boiler can enter this state from the "stopped" state by the operator's command, provided that the water supply path and the fuel supply path are ready for operation (all necessary valves and gates are open, including manual ones). Also, the drum is filled with water to the operating level, the smoke exhauster and fan are working, the vacuum in the boiler furnace and the air pressure are within the limits required for ignition. Further, in this state, the ignition procedure should be started, after which a controlled, stable fuel combustion mode should occur in the boiler furnace. After this, a transition to the "warm-up" or "stopped" state may occur, if there are certain reasons.

"Warm-up" state. In this state, the boiler warms up and the parameters gradually increase to operating values, and emergency protection systems are activated. From this state, the boiler can go:

– to the "normal stop" state at the operator's command;
– to the "emergency stop" state, if one of the parameters controlled by the emergency protection system is not normal;
– to the "operation" state, provided that the boiler has reached operating parameters and the state of all parameters is normal and the main regulators (level, pressure, vacuum, fuel/air ratio) are switched to automatic mode, and the steam valves (manual and electrified) are open.

"Operation" state. This state is characterized by the boiler operating at nominal parameters, i. e. the steam generation process is underway. This is considered the main state of the boiler. From this state, the boiler can go into the "hot stop" state (standby mode) at the operator's command or automatically when certain conditions are reached. The boiler can also go into the "emergency stop" state when the emergency protection system is triggered or at the operator's command.

"Emergency stop" state. This state is characterized by the actions of the boiler protection system and operational personnel to prevent a man-made accident (explosion, rupture of pipelines, destruction of boiler structures). In this state, emergency protection procedures are launched to stop the fuel combustion process in the boiler furnace as soon as possible and reduce the main parameters of the boiler to safe levels. After performing this procedure, the boiler goes into the "stopped" state.

"Hot normal stop" state. The boiler can be in this state for a certain time if it is necessary to reduce its performance or if its main parameters have reached the maximum permissible level. At the same time, the intensity of the combustion process in the furnace decreases or combustion stops completely. If the boiler has not had time to cool down, and its pressure and level are within the operating limits, the operator can return the boiler to the "operation" state with the appropriate command, or this can happen automatically if pre-set conditions are triggered. Otherwise, the boiler will go into the "normal stop" state.

"Full normal stop" state. The "normal stop" state is characterized by a smooth decrease in the intensity of the fuel combustion process and subsequently – the cessation of fuel supply to the furnace, which leads to a decrease in boiler performance and its safe stop. At the same time, the values of the main parameters decrease to the limits sufficient for the transition to the "stopped" state.

To transition between boiler states, certain predetermined procedures (ignition or emergency protection), automated or manual, must be performed by the operator with field equipment (gates, valves, etc.). Actions during the execution of these procedures will change the state of the equipment used during boiler operation.

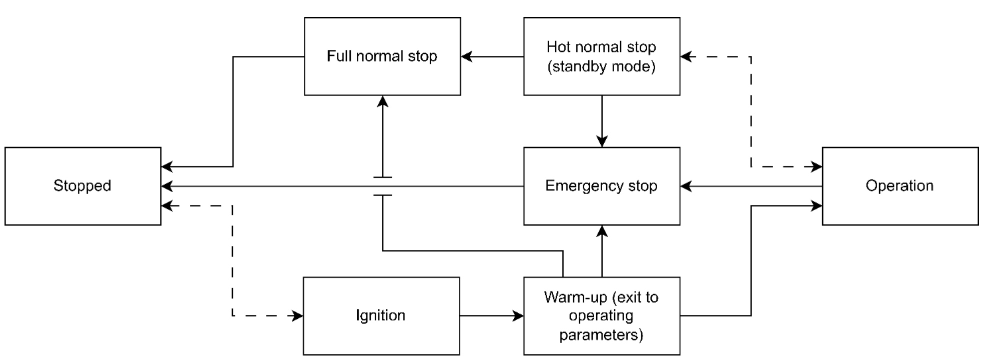

Fig. 5. Boiler state diagram

3.8. Application of fuzzy sets for decision-making

Even the most complex objects are successfully controlled by experienced operators based on intuitive "IF...THEN" rules that do not have clear information support. The control strategy used by the operator can be formulated as a set of rules that are quite simple to execute manually, but difficult to formalize using conventional algorithms. The main reason for this is the operator's use of qualitative, rather than quantitative, assessments when describing decision-making conditions. It is for the decision-making module that a fuzzy set apparatus can be applied, the data to which will come from the machine vision subsystem and simplify the decision-making algorithm for the operator [10]. The structural diagram of the fuzzy set apparatus can be interpreted as a system with a fuzzy controller (Fig. 6).

The procedure for parameter fuzzification is the conversion of the current values of the input variables of the boiler, including those from the machine vision subsystem, into linguistic values (a numerical range of parameters is possible, which are qualitatively characterized by the linguistic values "small", "medium", "large"). Each linguistic value is interpreted as a fuzzy set and described by a membership function. In this way, qualitative assessments are converted into quantitative ones, that is, each current numerical value of the process variable corresponds to the degree of membership in that fuzzy subset that symbolizes a specific linguistic variable. Membership functions overlap each other, therefore, for each variable, several membership functions can evaluate different truth values that are different from zero.

The logical solution is formed on the basis of the linguistic rule "IF A, THEN B" – a "working rule". The "IF" part (precondition) can mean a conjugation of any complexity of logical operations. The "THAT" part (decision, conclusion) is the definition of a linguistic value for the controller's output action. In this case, the rules are formed in such a way that a result is achieved, at which for any linguistic value of control at least one of the rules is accepted.

Traditional methods of control theory are modified taking into account the possibilities of fuzzy logic, such as: assessing the reliability of systems; identifying equipment states (diagnostics); identifying fuzzy regression models. Considerable attention is paid to the application of fuzzy logic to control complex technological objects, such as boiler plants.

This type of information can be used to support decision-making at boiler plants during their starting and stopping, since these processes are often accompanied by a number of manual non-automated operations. The proposed decision-making and support system also helps the operator make decisions based on equipment states, including taking into account manual operations.

The approach considered above makes it possible to simplify the work of experts to identify the main dependencies between the input and output variables of the processes of starting and stopping boiler plants. Since, having only experimental statistics of the operation of individual tracts, it is possible to form a knowledge base of an intelligent control system based on the obtained knowledge base. Further, this knowledge from the base can be interpreted through linguistic variables of a fuzzy set and presented to the operator in the form of prompts and ready-made solutions. At this stage, the corresponding procedure is performed, which is filled with proposed solutions and sequences for implementing starting operations or boiler stopping operations. Also, if there are any operations that the operator must perform manually, it performs them, verifying and confirming each proposed step.

Thus, the procedure and all manual operations are performed step by step, under the control of the DSS algorithm (Fig. 7).

The limitations of the study are that the results can only be applied to boiler plants. To apply such decision support systems to other technological plants, it will be necessary to update or create a new rule base.

Martial law conditions significantly affected the research, since regular air raids forced to leave industrial sites and continue work in shelters. For this, it was necessary to ensure the possibility of remote communication, provided that the enterprise's information network allowed such interaction. All this contributed to an increase in the time of research and obtaining results. Also, constant shelling from the Russian Federation prompted energy enterprises to increase the level of safety during the operation of their equipment, which in turn increased demand and made the decision support systems that we cover in our study more relevant.

Prospects for further research can be considered the creation of a more universal DSS structure for use at facilities of other types and in other industries. Also, in the future is the development of tools to simplify the deployment of such systems, updating the rule base, in accordance with the needs of the control object and tools to simplify the training of classifiers of the machine vision subsystem.

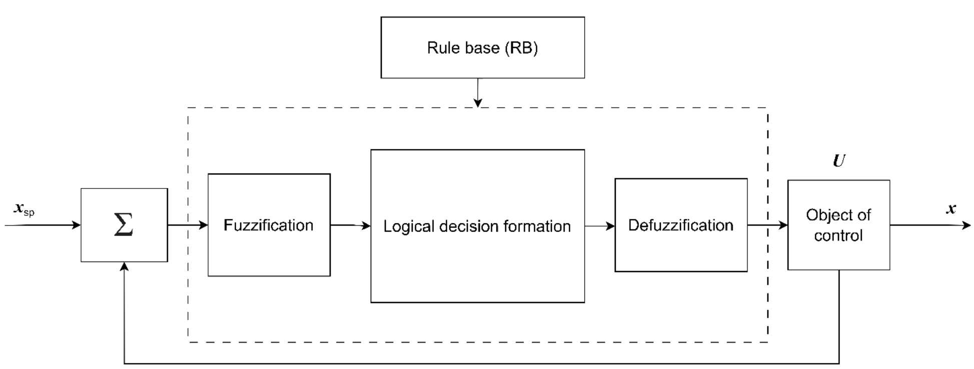

Fig. 6. Structure of a system with a fuzzy set apparatus

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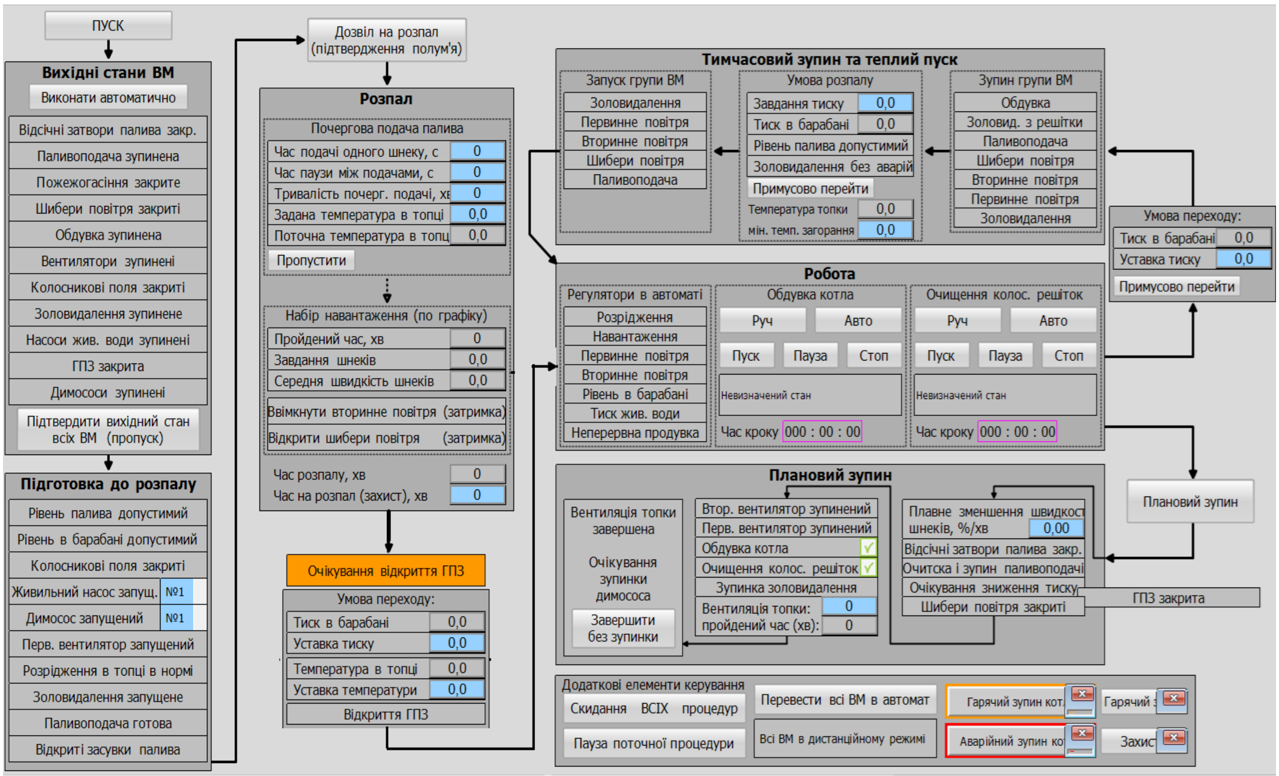

Fig. 7. Example of DSS procedure for starting and stopping a power boiler

4. Conclusions

The work shows that DSS is an important element for effective work in boiler houses and thermal power plants, where operators face a large physical and cognitive load when performing complex operations. Despite the presence of automated systems, part of the work is still performed manually, which creates certain limitations in comprehensive monitoring and process management. This can lead to loss of personnel concentration, reduced accuracy and possible errors, especially in stressful situations. The implementation of modern DSS, including machine vision subsystems, will allow monitoring the state of both automated and manual mechanisms in real time, providing more complete information about the state of the equipment. This will help reduce the cognitive load on operators, promptly detect malfunctions and make timely informed decisions, which increases the safety, efficiency and reliability of boiler operation.

This study presents the conceptual structure of DSS for optimizing boiler plant management in critical operating modes. The proposed approaches allow reducing dependence on the human factor, increasing safety and efficiency, and also contributing to the further development of automation technologies in the field of industrial energy. The results of the work may be useful for production automation engineers, researchers and specialists involved in the design of energy facility control systems.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other nature, which could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors used artificial intelligence technologies within the permissible framework to provide their own verified data, which is described in the research methodology section.

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✉***Yevhenii Bondarenko**, PhD Student, Department of Automation and Computer Technologies of Control Systems named after Prof. A. P. Ladanyuk, National University of Food Technologies, Kyiv, Ukraine, e-mail: evgen.bond98@gmail.com, ORCID: https://orcid.org/0009-0008-9594-2418*

***Roman Karpenko**, PhD Student, Department of Automation and Computer Technologies of Control Systems named after Prof. A. P. Ladanyuk, National University of Food Technologies, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0006-3873-3455*

✉*Corresponding author*