UDC 681.5
DOI: 10.15587/2706-5448.2026.363894

Petro Kachanov,
Mykola Tarasenko

DEVELOPMENT OF A COORDINATED SYSTEM FOR AUTOMATIC CONTROL OF THE COMBUSTION PROCESS OF A BOILER UNIT WITH CORRECTION FOR OXYGEN CONTENT

The object of research is the automatic control system for the boiler-unit combustion process, which coordinates fuel and air supply, stabilizes furnace draft, and provides slow correction of excess air based on the measured oxygen content in flue gases. The system coordinates the supply of fuel and air, applying a gradual correction of excess air based on the measured oxygen content in the flue gases. The main problem is to ensure coordinated control of the fuel, air and draft channels under the conditions of plant inertia, transport delays, actuator limitations, changes in fuel properties and load effects. To solve this problem, a control structure is proposed with a division into fast and slow levels, coordinated with each other. In this structure, the fast control level generates a setpoint air flow rate using the fuel flow rate signal. The slower control level applies a limited correction of the fuel-air ratio coefficient in accordance with the deviation of the oxygen concentration from its setpoint. The proposed control structure was tested using simulation in MATLAB/Simulink (The MathWorks, Inc., USA). The obtained transient characteristics demonstrate the system's response to a change in the set value of the thermal load. The control signal of the fuel channel remained within the permissible range, which confirms the correct operation of the constraints and the absence of accumulation of the integral component beyond the physically permissible limits. The system shows effective compensation of load disturbances and restoration of the required oxygen level without persistent fluctuations. The obtained results demonstrate a clear separation between fast flow coordination and slow oxygen-based correction. Thanks to this separation, the gas analyzer channel does not degrade the dynamic characteristics of the faster control loops. The research results can be used for modernization and tuning of combustion control systems in boiler units of thermal power plants and industrial boiler houses.

Keywords: *automatic control system, Simulink, simulation model, boiler unit, fuel-air ratio.*

Received: 05.01.2026
Received in revised form: 22.05.2026
Accepted: 03.06.2026
Published: 09.06.2026

How to cite
Kachanov, P., Tarasenko, M. (2026). Development of a coordinated system for automatic control of the combustion process of a boiler unit with correction for oxygen content. Technology Audit and Production Reserves, 4 (2 (90)), 6–13. https://doi.org/10.15587/2706-5448.2026.363894

1. Introduction

Automation of technological processes in thermal power engineering is one of the main ways to improve the reliability, efficiency, and environmental safety of boiler units. Boiler control engineering is examined in [1] from the perspective of practical implementation. The source gives examples of controller configuration and tuning, valve sizing, and transmitter specification, which makes it useful for supporting the applied nature of boiler ACS development. However, the available description does not make it possible to treat this source as direct evidence for the interaction between fast fuel-air coordination and slow oxygen correction. For this reason, that issue requires separate simulation-based analysis.

In both classical and modern literature, a boiler unit is described as a complex multivariable control object. It involves the simultaneous conversion of the chemical energy of fuel into heat, heat transfer from combustion products to the working fluid, and mass transfer in the gas path and steam-water circuit. These processes develop at different rates, include considerable delays and inertia, and are strongly nonlinear. Their behavior depends on boiler load, fuel composition, excess-air coefficient, and the condition of the heating surfaces [1, 2].

In general, stable boiler operation depends on three closely connected control tasks. The first task is regulating the thermal load, usually through steam pressure or another heat-balance indicator. The second task is controlling the fuel-air ratio to ensure efficient and complete combustion. The third task is maintaining draft, or negative pressure, in the furnace and flue-gas path. These loops inevitably influence one another through the plant. A change in fuel feed affects not only heat release, but also air demand, flue-gas composition, and gas-exchange conditions. Similarly, a change in airflow influences furnace pressure and heat transfer, while a change in draft alters the flow of combustion products and therefore affects combustion itself [1, 3].

In industrial boiler systems, combustion ACS is usually designed as a coordinated group of control loops rather than as a single universal controller. Traditional control schemes typically use a boiler master, or load controller, based on steam pressure or another integral heat-balance variable. This controller generates a fuel-demand signal, which is then implemented through a subordinate fuel-flow loop. The required airflow is formed from the fuel signal by means of a ratio station, or a ratio/bias module, because this approach helps maintain safe fuel-air mixing while preserving acceptable dynamic response during rapid load changes. At the same time, a draft-control loop regulates the induced-draft fan or damper position to keep furnace pressure within safe limits and stabilize gas-path flow conditions. This multi-loop structure is not just a standard design choice. It mirrors the real physical behavior of boiler dynamics, where the slow thermal inertia of the steam-water circuit operates alongside faster aerodynamic, fuel, and air-actuator responses, as well as transport delays in the gas path and measurement channels [1–3].

Automation of the DKVr-10-13 (Monastyryshche Boiler Equipment Plant "Energometmash", Ukraine) boiler plant for boiler rooms of food industry enterprises is analyzed in [4]. The authors emphasize the importance of improving automatic steam-production control in order to increase energy efficiency and reduce energy consumption. However, this work is focused on boiler automation for a specific industrial application and does not fully address the coordinated control of fuel supply, air supply, oxygen correction, and furnace draft in a single combustion-process ACS.

In the paper [5], a combustion-control approach is proposed that combines parallel air-fuel control with cross-limiting control. The research shows that such a combination can improve air-fuel ratio control and reduce problems typical of conventional systems during sudden load changes. However, the work does not consider slow oxygen-based correction as a separate supervisory layer and does not analyze its interaction with the faster air-flow coordination loop.

Recent researches have shown an increasing interest in developing coordination constraints using modern control methods. For example, additional air-fuel ratio control based on dynamic matrix control has been proposed [6]. This approach has led to improved emission-related performance while maintaining the traditional safety coordination used in industrial systems. In this method, the base ratio and cross-constraint logic are treated as hard constraints, while the predictive control layer provides small corrective changes to improve steady-state operation without disrupting faster control cycles. This approach is consistent with the principle underlying the robust design of combustion ACS. These systems should maintain a robust basic structure built around fuel and air control cycles and a constant vacuum level in the furnace. Optimization and control functions should be introduced only as an add-on, and not replace the entire system with a single, highly model-dependent controller [1, 3].

In [7], the authors investigate the energy savings in an oxygen-controlled boiler room equipped with a variable-speed fan drive. However, the research primarily focuses on the energy impact of oxygen control and fan speed control, while the dynamic structure of the combustion ACS and its response to load changes are not the main areas of analysis.

One of the most common control mechanisms is oxygen control, or O_2 control, where the quality of the combustion process is determined based on the measured oxygen content in the flue gases. Its main advantage is that oxygen serves as a reliable indicator of excess air. It can also indirectly capture changes in fuel composition, air leakage, burner wear, and gas path conditions [1, 2, 7]. However, O_2 control should be implemented with caution. Gas analyzers often introduce significant delays and inertia, and if the control loop is set too aggressively, these delays can weaken the stability of the fuel-air ratio control. Field studies show that properly designed oxygen control, especially in combination with improved airflow control, can provide measurable energy savings and increase the overall efficiency of the boiler plant. Maintaining stability across operating modes is another important challenge. Boiler subsystems can experience changes in gain and time constants depending on changes in load and operating conditions. As a result, fixed controller settings can become less effective and, in some cases, even approach unstable behavior when operating modes change [4, 8].

As a practical way to maintain acceptable control quality under such fluctuations, parametric adaptation of controllers has been proposed [9]. It is achieved by adjusting the controller parameters according to the observed operating conditions and plant dynamics. The authors show that the dynamic characteristics of boiler circuits vary depending on the load of the power unit, and that controller adaptation can improve control efficiency. However, their research focuses on the steam-water path and temperature control of boiler units with supercritical parameters.

Analysis of typical combustion control system schemes described in the literature shows that the most common industrial solution is a combined control structure. Therefore, a coordinated combustion control system that includes fuel-air ratio control, oxygen correction and draft stabilization requires a separate research. In this scheme, the ratio control station provides the main coordination between the fuel and air flows. More accurate control of excess air is achieved by correction based on the measured oxygen content in the flue gases. The problems considered confirm the feasibility of using coordinated two-time architectures. A fast control loop for safety and transient response, and a slower correction loop for efficiency and stability under uncertainty. Additionally, the rarefaction in the furnace is controlled by a draft loop. To improve transient behavior, a direct or dynamic coupling between the air and draft control loops can also be introduced [1, 3, 4, 8].

Several important problems still remain in modern automatic combustion control systems for boilers. One of the main problems is the uncertainty and variability of fuel properties and combustion conditions, which makes it difficult to maintain efficiency indicators under load changes [4]. Another important factor is the presence of strong cross-coupling between the air and draft channels. During transient operating conditions, these interactions can lead to air-fuel ratios exceeding safe limits. For this reason, the literature supports the use of cross-constraint-based consistent loop control [5], as well as methods for representing these constraints in optimal or predictive control formulations [6].

Overall, the reviewed sources confirm that boiler combustion control is practically important and technically complex. Existing research covers classical boiler control structures, air-fuel ratio coordination, cross-limiting methods, oxygen control efficiency, predictive supplementary control, and PI-controller adaptation. However, the literature does not fully address the development and formal description of a coordinated combustion ACS that combines fast fuel-air coordination, slow oxygen correction, draft stabilization, and simulation-based transient behavior assessment.

The object of research is the automatic control system for the boiler-unit combustion process, which coordinates fuel and air supply, stabilizes furnace draft, and provides slow correction of excess air based on the measured oxygen content in flue gases.

The aim of research is to develop a coordinated automatic control system for the boiler-unit combustion process that ensures thermal-load stabilization, economically justified excess-air control, and draft stabilization while accounting for cross-couplings and dynamic properties of the controlled plant.

To achieve this aim, the following objectives were set:

1. To analyze the boiler-unit combustion process and determine its main variables, disturbances, and cross-couplings.
2. To substantiate the structure of coordinated fuel-air control with slow oxygen-based correction and furnace draft stabilization.
3. To develop a simulation model of the combustion-process ACS.
4. To evaluate the transient behavior of the proposed ACS under load setpoint changes and disturbances.

2. Materials and Methods

The research was conducted using simulation modeling in MATLAB/Simulink (The MathWorks, Inc., USA). During the research, a block diagram of the control object and the automatic control system was developed.

The control object was represented using simplified dynamic elements that describe the basic behavior of the fuel and air paths. The model also reflects how changes in the air-fuel ratio affect the oxygen concentration in the flue gases. This level of detail is sufficient to study the interaction between control loops and assess the effectiveness of coordination between control channels.

The automatic control system consists of fast and slow control loops. The fast loop generates an air flow rate set point based on the measured fuel flow rate. The slow loop corrects the air flow rate based on the oxygen values in the flue gases.

The subordinate fuel- and air-flow loops were controlled using PI controllers. The oxygen-correction loop was also PI-based, but it was intentionally tuned to operate much more slowly in order to avoid destabilizing interaction with the faster coordination dynamics.

To ensure physically feasible control actions and stable recovery after constraint activation, amplitude limiting and, where required, rate limiting was applied to the supervisory correction signals. Anti-windup protection was also included for PI controllers operating under saturation.

The evaluation procedure involved simulating typical operating scenarios, including load setpoint changes and disturbances. During the simulations, the time responses of the main variables were recorded. The transient behavior, coordination quality, and compliance with constraints were then assessed under identical test conditions.

3. Results and Discussion

3.1. Analysis of the boiler-unit combustion process and determination of its main variables, disturbances, and cross-couplings

The controlled object is a drum-type boiler unit viewed through the combustion process taking place in the furnace and the adjoining sections of the flue-gas path. This is the area where heat is produced and combustion products are carried toward the heating surfaces. The boiler unit includes a furnace chamber fitted with burners or nozzle devices, along with systems for fuel supply and air supply. The air-supply system consists of forced-draft fans and air ducts, while the combustion-product removal system includes gas ducts and induced-draft fans. Heat-exchange surfaces are also part of the unit, allowing heat to be transferred to the working fluid.

From the standpoint of automatic control theory, the boiler unit can be regarded as a multivariable plant with distributed parameters. Its main characteristic features are high thermal storage capacity, which results in slow dynamic behavior; transport and transient delays in the gas path and measurement channels, including the O_2-measurement channel; nonlinear steady-state characteristics under changing load conditions; actuator limitations; and cross-couplings between individual control subchannels.

Within the combustion process, the key manipulated variables (inputs) are defined as: fuel feed to the furnace, air flow supplied to the furnace, and the intensity of combustion-products removal (action on the induced-draft fan or damper).

The main controlled variables of the combustion ACS are steam pressure, oxygen content in the flue gases, and furnace negative pressure. Steam pressure is used as an integral parameter of the boiler thermal balance. Oxygen content characterizes the excess-air level. Furnace negative pressure reflects the consistency of the draft and forced-draft operating modes.

Disturbances are divided into external and internal. External disturbances include changes in consumer load (steam take-off) and variations in air parameters. Internal disturbances include changes in fuel quality, instability of fuel feeding, air in-leakage, and changes in the draft/forced-draft operating mode. Variability of fuel composition and its lower heating value is a determining factor that justifies correction of the "fuel-air" ratio based on O_2.

Control challenges are driven by the simultaneous action of two groups of requirements: ensuring safe operating modes (flame stability, prevention of hazardous mixtures, and compliance with constraints) and ensuring efficiency (minimization of stack losses and losses due to incomplete combustion).

Maintaining the specified "fuel-air" ratio is a necessary condition for complete combustion; however, the optimal excess-air level changes with load and fuel properties. Direct stabilization during transients is complicated by the inertia of the gas path and measurement delays; therefore, a combined approach is practically justified: fast coordination of flow rates and slow trim adjustment under steady-state conditions.

The furnace negative-pressure loop must ensure draft constancy when air and fuel flows change. Since a change in forced draft alters the flue-gas flow rate, it is advisable to provide the option of a feedforward (dynamic) action from the air loop to the draft loop.

The obtained result indicates that the combustion process should be treated as a multivariable object with interconnected fuel, air, and draft channels. In contrast to simplified approaches that describe the system as a set of independent local control loops, this representation highlights the cross-couplings that occur during transient operation. However, this result is limited by the fact that the object is described using dominant dynamic relationships rather than a detailed spatial model of the furnace. Further research should therefore focus on experimentally identifying these relationships under different boiler loads and for various fuel types.

3.2. Substantiation of the structure of coordinated fuel-air control with slow oxygen-based correction and furnace draft stabilization

The ACS synthesis is performed by constructing a coordinated control structure for fuel and air flow rates with O_2 correction. The starting point is the concept of decomposing the problem into two time scales. The fast layer provides coordination of the air flow rate F_a with the current/set fuel feed F_f. The slow layer performs correction based on the deviation of oxygen content O_2 in the flue gases ($O_{2\ trim}$), which compensates for uncertainties in fuel composition, air in-leakage, and changes in mixing conditions.

Fig. 1 shows a generalized model of the closed-loop air-flow control as part of the controller, actuator, and measurement channel.

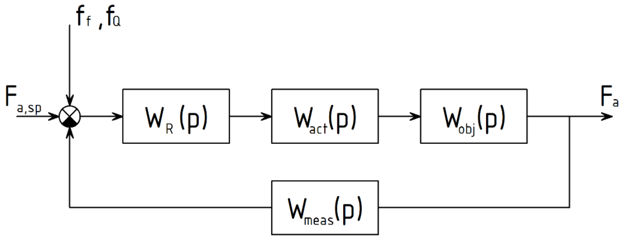

Fig. 1. Generalized single-loop ACS diagram

The diagram represents a generalized closed-loop air-flow control system for F_a in operator form. The summing junction receives the air-flow setpoint $F_{a,sp}$, generated by the flow-coordination module, and the feedback signal from the measurement channel. The additional summing-junction inputs f_f and f_Q are interpreted as equivalent disturbances that account for the influence of changes in fuel flow rate (the "fuel-air" cross-coupling) and changes in thermal load/process conditions (changes in aerodynamic resistance, air density, forced-draft mode, etc.) on the controlled variable.

The error signal is processed by the controller $W_p(p)$, after which the control action is applied to the actuator $W_{act}(p)$ (a damper, a variable-frequency fan drive, or another final control element). The plant dynamics $W_{obj}(p)$ describe the transformation of the control signal into the air flow rate in the air duct/at the furnace inlet, taking into account inertia and possible transport delay. The measurement block $W_{meas}(p)$ models the inertia and filtering of the flow sensor and transmitter, forming the measured signal $F_{a,meas}$ in the feedback path. Thus, the loop provides setpoint tracking for F_a and suppression of equivalent disturbances due to negative feedback.

Fig. 2 presents a functional diagram of fuel-air coordination with slow O_2 correction. The diagram reflects the functional organization of coordinated control in the "fuel-air" subsystem with correction based on the oxygen content in the flue gases.

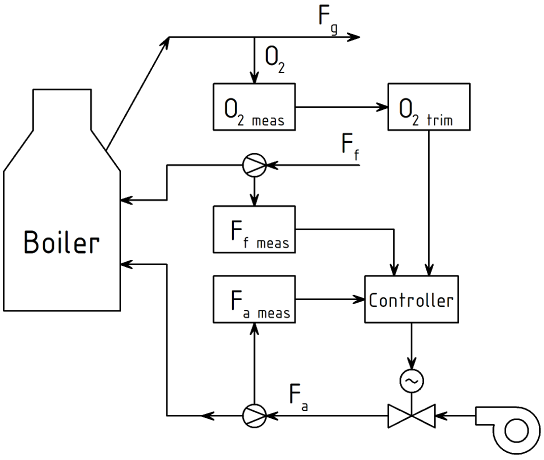

Fig. 2. Structure of the fuel-air coordination system with O_2 correction

The fuel flow rate F_f (signal $F_{f\,meas}$) is used as the leading variable for generating the air-flow setpoint F_a according to a coordination law, which ensures rapid compliance with a safe "fuel-air" ratio during load transients.

The air flow rate F_a (signal $F_{a\,meas}$) in a fast subordinate loop implemented by the air-path controller (block Controller), which drives the forced-draft final control element (damper/fan drive).

The proposed scheme includes a slow oxygen correction loop to increase efficiency and take into account changes in fuel composition and air leakage. The oxygen content in the flue gases is measured by the $O_{2\,meas}$ block and compared with a setpoint value. Based on the deviation, the $O_{2\,meas}$ block generates a setpoint correction. Since the gas analyzer has a significant transport delay and inertia, the $O_{2\,trim}$ loop is configured as a slow control loop. Its corrective action is limited in magnitude and, if necessary, in speed, so as not to reduce the stability margin of the fast control loop.

The coordinated operation of these two loops performs two complementary functions. First, it provides a fast response to changes in fuel feed by forming the air-flow setpoint $F_{a,sp}$ in proportion to the fuel flow F_f. Second, it stabilizes the excess-air indicator under quasi-steady operating conditions by using the measured O_2 concentration to gradually adjust the ratio coefficient.

When a fast internal loop, such as an air flow loop, tracks a setpoint generated by an external coordination or correction mechanism, the internal loop must be several times faster and sufficiently aperiodic. Under these conditions, it can be considered as a quasi-static element from the perspective of the external loop [10]. This requirement is particularly important in combustion control, because the oxygen-measurement channel usually adds extra phase lag due to transport delay and analyzer inertia. If the oxygen feedback loop is closed with a bandwidth similar to that of the air-flow loop, delayed feedback is effectively introduced into the setpoint-generation path, increasing the risk of oscillatory behavior [3, 9]. For this reason, the O_2-trim function in the proposed structure is deliberately implemented as a slow supervisory correction with a limited influence on the fast coordination dynamics.

The use of PI controllers in subordinate flow loops and in the O_2-correction loop is consistent with the widespread industrial application of PID-family controllers in process control. Their use is also supported by well-established tuning approaches for systems affected by delay, actuator constraints, and external disturbances. In flow-control loops, PI control is often sufficient because flow measurements are generally less noisy than composition measurements. Moreover, the dynamics of controlled flow channels can usually be approximated by low-order inertial models, sometimes with an effective delay.

PI control can also be applied to the oxygen-correction loop, as long as its bandwidth is kept low and its output is properly limited. In practical boiler-control systems, constraints are an inherent part of operation. Final control elements, including dampers, fan drives, and valves, are limited in both amplitude and rate of movement. In coordinated combustion-control schemes, additional selector logic, such as cross-limiting, may also change the effective setpoints to preserve safe operating conditions.

Integral tuning is an important factor that can degrade control performance. When an actuator or selector element reaches saturation, the controller integrator can continue to accumulate a control demand that is physically unfeasible. Once the limit is removed, this accumulated integral action can lead to overshoot, longer transients, and slower recovery. For this reason, the controller implementation should include tuning protection and explicit limits on the correction signals [9, 10]. The nominal ratio factor k_0 provides a direct relationship between air demand and fuel consumption. The correction term $\Delta(p)$, generated by the O_2 tuning loop, acts as a slow offset control. Its purpose is to compensate for changes in fuel quality and air leakage.

Finally, since boiler characteristics change with operating conditions, the proposed architecture is also suitable for gradual adaptation of controller parameters across different load ranges. Parametric adaptation methods for PI controllers in boiler units have been reported as an effective way to maintain stable and acceptable dynamic behavior when process gain and time constants vary with load or operating mode [11]. Within the present framework, such adaptation can be introduced without redesigning the entire control structure. It may be applied to the subordinate flow-control loops or to the steam-pressure loop, while the overall coordination logic and the slow supervisory role of oxygen correction remain unchanged.

The air-flow setpoint $F_{a,sp}(p)$ is formed as a function of the current (or commanded) fuel flow rate

$$F_{a,sp}(p)=k_r(p)F_f(p). \tag{1}$$

The fuel-air ratio coefficient $k_r(p)$ is defined as

$$k_r(p)=k_{r0}+\Delta k(p), \tag{2}$$

where k_{r0} – the nominal value of the coefficient; $\Delta k(p)$ – the coefficient correction generated based on the oxygen meter (O_2 analyzer) signal.

The $O_{2\,trim}$ loop is intended to compensate for uncertainties associated with changes in fuel composition, air in-leakage, drift of the base coefficient k_{r0}, burner wear, and changes in mixing conditions. The oxygen control error $e_{O_2}(p)$ is defined as

$$e_{O_2}(p)=O_{2sp}(p)-O_2(p), \tag{3}$$

where $O_{2sp}(p)$ – the specified value (setpoint) of the oxygen volumetric fraction in the flue gases; $O_2(p)$ – the measured oxygen value at the gas analyzer output, taking into account the inertia and delay of the measurement channel.

The ratio-coefficient correction is generated according to a PI law with small gains [9, 12]

$$\Delta k(p)=K_{trim}\frac{T_{itrim}p+1}{T_{itrim}p}e_{O_2}(p), \tag{4}$$

where K_{trim} – the loop gain (proportional component) of the $O_{2\,trim}$ loop; T_{itrim} – the integration time constant in the $O_{2\,trim}$ loop.

Given the substantial delay and inertia of the gas analyzer, it is advisable to apply preliminary filtering of the signal using a first-order (inertial) element [10]

$$W_f(p)=\frac{1}{T_f p+1}, \tag{5}$$

where T_f – the filter time constant.

For analysis and tuning of the subordinate air-flow loop F_a, the generalized block diagram (Fig. 1) is used.

Then, the closed-loop transfer function for the setpoint channel is given by the expression

$$W_{cl}(p)=\frac{W_R(p)W_{act}(p)W_{obj}(p)}{W_R(p)W_{act}(p)W_{obj}(p)W_{meas}(p)+1}. \tag{6}$$

The plant transfer function can be represented by a FOPDT model

$$W_{obj}(p)=\frac{k}{Tp+1}e^{-\tau p}. \tag{7}$$

Tuning is expedient to perform sequentially. First, sufficiently fast and aperiodic, or non-oscillatory, setpoint tracking is ensured in the subordinate air-flow loop F_a. This is achieved by selecting a target transient time noticeably smaller than the characteristic time of boiler thermal-state changes. The target transient time is also smaller than the effective time constant of the O_2 channel. After that, O_2-trim is introduced as a slow supervisory layer. Its dynamics are set several times slower than the dynamics of the F_a loop. This prevents mutual oscillations caused by the gas analyzer delay.

The obtained result confirms that it is feasible to separate fast fuel-air coordination from slower oxygen-based correction. A distinctive feature of the proposed structure is that the oxygen channel is used only as a bounded supervisory correction and does not replace the faster air-flow control loop. Compared with conventional ratio-control schemes, the proposed structure also compensates for gradual changes in fuel quality and air-path conditions. However, the draft loop is considered only at a functional level, which limits the completeness of the model. Further work should therefore include a more detailed representation of the draft and flue-gas path.

3.3. Development of a simulation model of the combustion-process ACS

The ACS was simulated in the MATLAB/Simulink environment. The overall ACS diagram is shown in Fig. 3. The overall simulation model is built as two interconnected subsystems: the Controller subsystem (Fig. 4), which contains the controllers, and the BoilerPlant subsystem (Fig. 5), which reproduces the dynamics of fuel and air supply as well as the effect of disturbances.

The Controller subsystem implements the combustion-control algorithms and generates the control actions u_f (fuel path) and u_a (air path). The air-flow setpoint $F_{a,sp}$ is formed based on the "fuel-air" ratio and the oxygen correction $O_{2\,trim}$.

The BoilerPlant subsystem models the boiler unit dynamics as the controlled plant for the combustion process. It accounts for the inertia of the final control elements in the fuel and air paths. It also describes the formation of the process outputs P_s and O_2. The model considers the "fuel-air" cross-couplings between the main combustion-control channels. It also accounts for disturbances, including changes in fuel quality f_Q and an external influence or draft disturbance f_f. In addition, the model includes load changes d_L as a separate disturbance input.

The simulation model made it possible to test the proposed control structure under the same operating conditions. Its main distinguishing feature is that it includes actuator saturation, rate limits, oxygen-channel inertia, and fuel-air cross-couplings. Compared with idealized simulation schemes, this model provides a closer representation of practical ACS implementation conditions. However, its limitation is that the model parameters were not identified using data from a specific industrial boiler unit. Further research should therefore focus on validating the model with experimental or operational data.

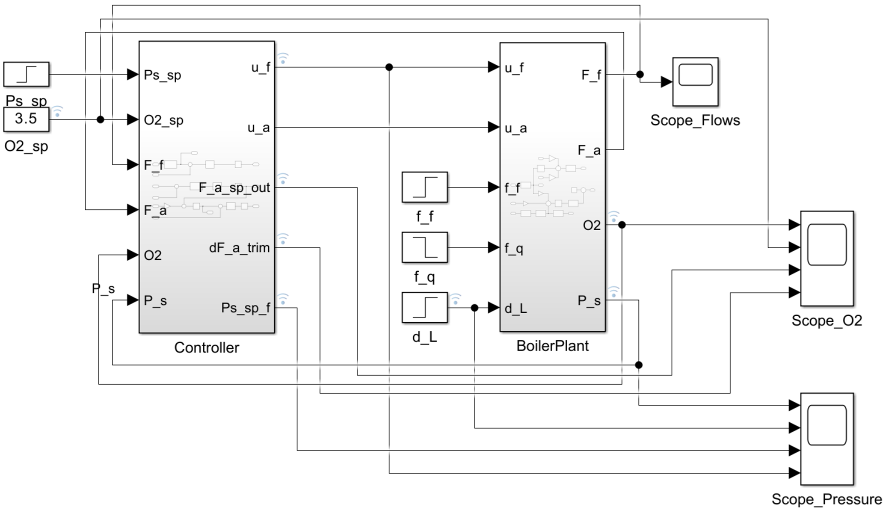

Fig. 3. Overall simulation model of the combustion-process ACS in Simulink

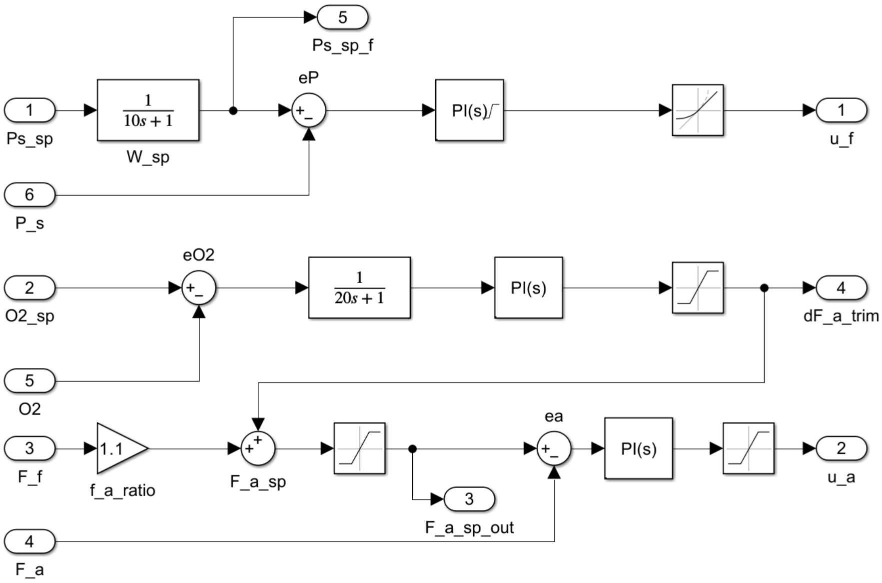

Fig. 4. Controller subsystem

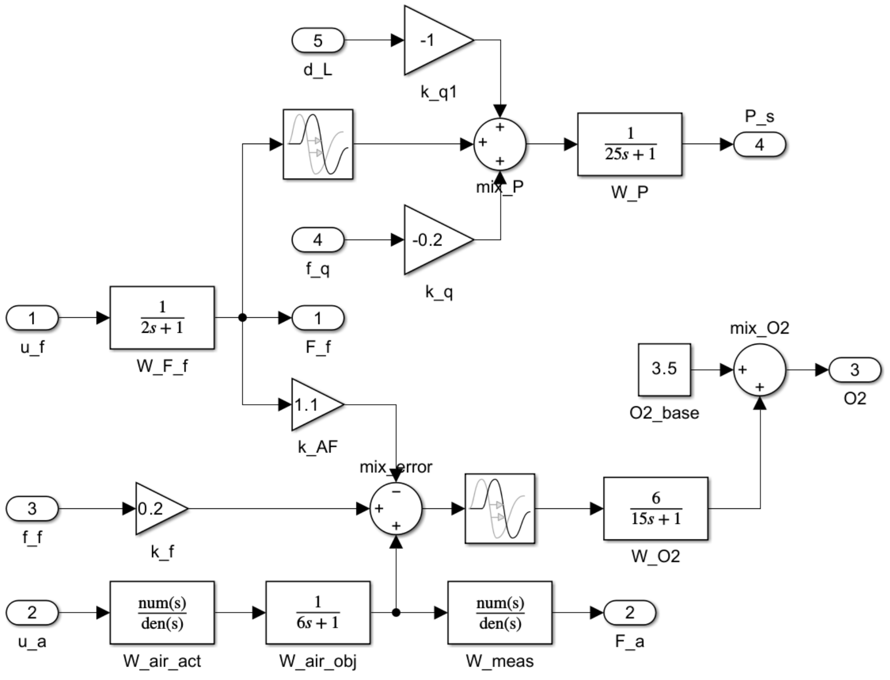

Fig. 5. BoilerPlant subsystem

3.4. Evaluation of the transient behavior of the proposed ACS under load setpoint changes and disturbances

Two plots corresponding to the key ACS loops are presented below: correction of the fuel-air ratio based on oxygen content (Fig. 6) and steam-pressure control (Fig. 7).

According to the simulation results, the oxygen volumetric fraction in the flue gases O_2 deviates from the oxygen setpoint $O_{2\,sp}$ after a change in operating mode, but returns to the specified level without loss of stability and without long-lasting oscillations. The correction signal $\Delta F_{a\ trim}$ has a limited amplitude. It also varies slowly relative to the fast steam-pressure, or load, loop. This behavior satisfies the requirements for gas-analyzer-based correction. It also prevents the overall control dynamics from being shifted toward the slower oxygen channel. The air-flow setpoint $F_{a,sp}$ is formed by the ratio loop and changes in a coordinated manner with the fuel-feed mode, while $O_{2\ trim}$ performs only fine trimming.

The obtained dependencies demonstrate tracking of the steam-pressure setpoint change $P_{s,sp}$ with a finite overshoot and subsequent settling of the steam pressure P_s near the specified value. At the moment when the load disturbance d_L is applied, a deviation of P_s is observed, which is compensated by the controller action via a change in the control signal applied to the fuel final control element u_f. At the same time, u_f does not exceed the range [0, 1], which confirms the absence of incorrect acceleration (windup) of the integral component beyond physically feasible control.

In contrast to simplified schemes, O_2 correction may be applied relatively fast or without explicit consideration of analyzer delay. In this work, O_2-trim is treated as a slow supervisory loop. This loop operates on a separate time scale. Such separation reduces the risk of undesirable interaction with the ratio, or coordination, loop.

In addition, unlike idealized models, the simulations explicitly account for saturation and rate limiting of control actions, making the results closer to typical industrial implementation conditions.

The transient responses demonstrate stable behavior of the proposed ACS under both a setpoint change and a load disturbance. Steam pressure reaches approximately 0.79 for a setpoint of 0.70, which corresponds to an overshoot of about 13–14%. After the load disturbance of 0.1 is applied at 160 s, the steam pressure returns close to 0.70 by around 220–230 s. The oxygen content decreases to about 3.03 and then gradually returns toward the setpoint level without persistent oscillations. However, these results are limited by the fact that they were obtained through simulation. Further research should therefore compare the proposed structure with conventional control methods and validate the results on real equipment.

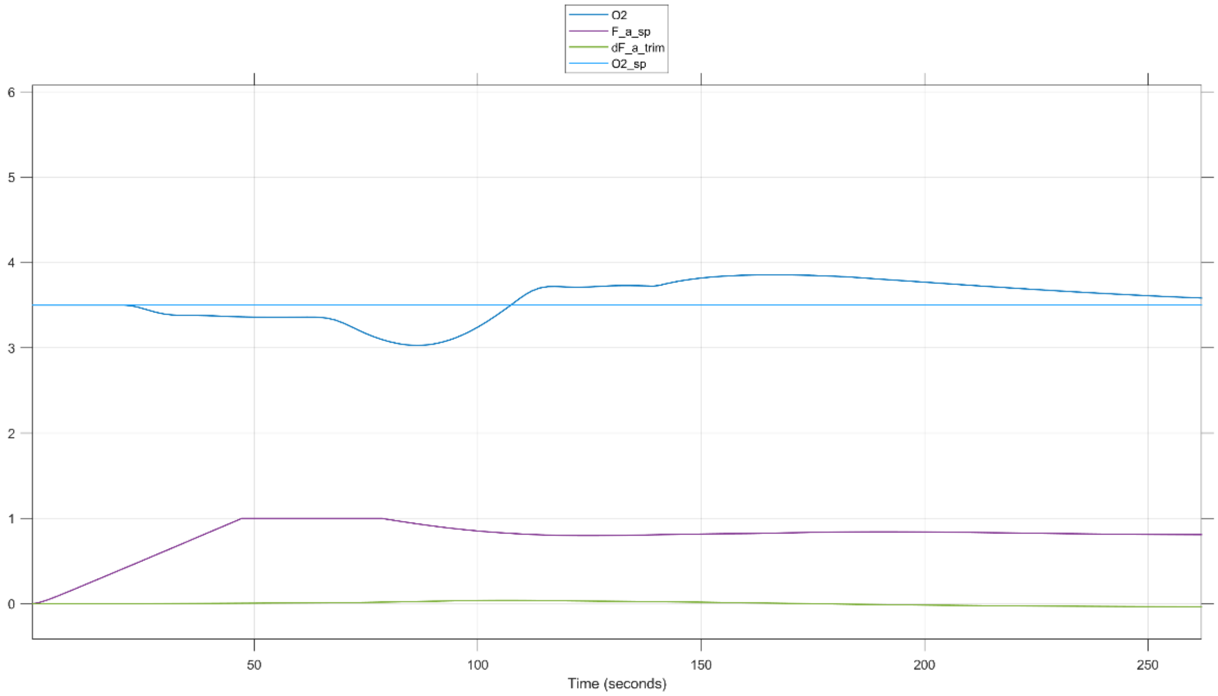

Fig. 6. Transient responses in the oxygen-correction loop

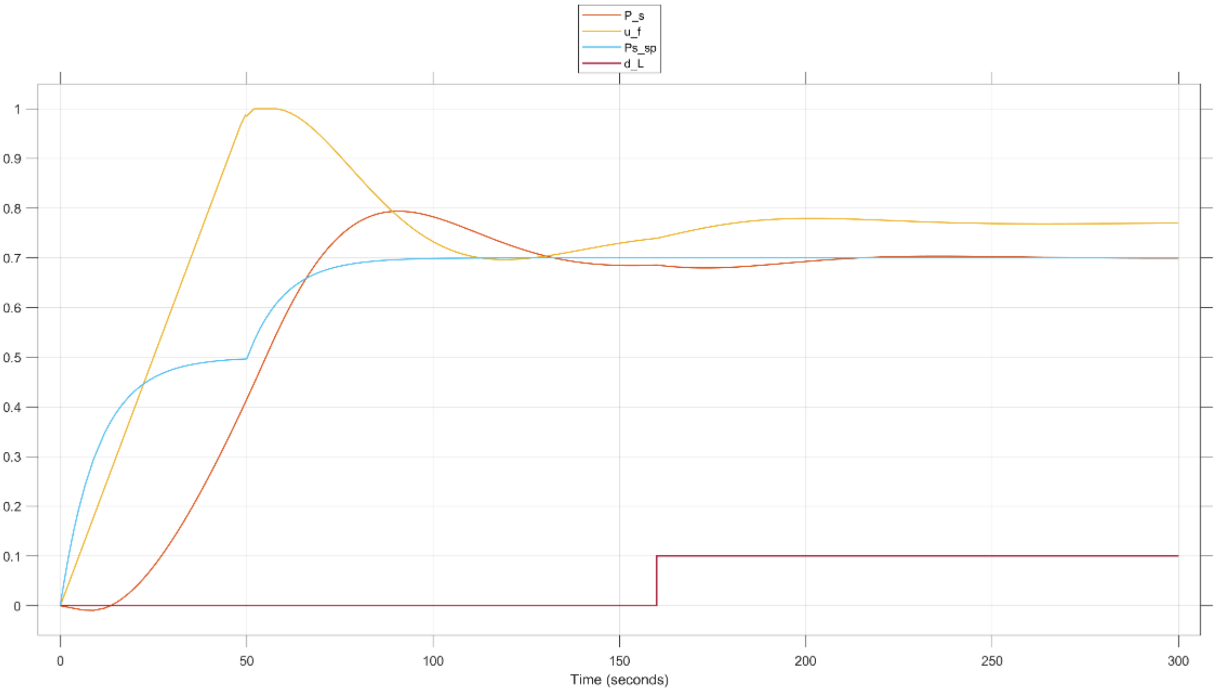

Fig. 7. Transient responses in the steam-pressure (load) loop

The proposed structure can be used for modernization and tuning of boiler combustion ACS in thermal power plants and boiler houses where both transient safety and steady-state efficiency are required. Fuel-air coordination via a ratio station combined with slow O_2-trim is well suited for DCS/PLC implementation: the fast layer prevents hazardous mixture deviations during load changes, while the slow trim helps maintain a more appropriate excess-air level under changes in fuel properties and air-path conditions. A further practical benefit is the explicit treatment of actuator constraints, which facilitates transferring tuning concepts from simulation to a real plant and reduces the risk of incorrect behavior under saturation.

Wartime conditions in Ukraine affected the organization and execution of the research, primarily by limiting access to industrial facilities and measurement infrastructure, complicating full-scale experimental testing, and introducing disruptions in power supply and communications. Consequently, the work relied on simulation modeling and analysis of typical operating scenarios, while incorporating realistic actuator constraints and measurement delays.

3.5. Limitations and directions for further research

The conducted research has a number of limitations that determine the limits of application of the obtained results and show what issues need to be resolved before the practical implementation of the proposed system.

The first limitation is related to the fact that the boiler unit model is built in a simplified form. It takes into account the main dynamic properties of the fuel and air channels, the inertia of measurement, the limitations of the actuators and the mutual influence of the fuel-air channels. However, the model does not consider in detail the heat transfer in the gas ducts, the change in aerodynamic resistance and the spatial distribution of temperature and oxygen concentration.

Another limitation concerns the rarefaction circuit in the furnace. In this work, it is considered at the functional level, as part of the general structure of coordinated control. At the same time, the dynamics of the gas path are not described in sufficient detail. In the future, it is necessary to expand the model and investigate how the change in air supply affects the rarefaction in the furnace during transient regimes.

The next limitation is that the model parameters were not obtained from the experimental data of a specific boiler unit. The results were obtained by simulation modeling. Experimental tests were not conducted due to limited access to industrial facilities, measuring infrastructure and conditions for long-term tests on operating equipment. The parameters used allow to verify the operability of the proposed control structure, but they cannot fully describe the behavior of a real object.

In conclusion, further development of the work should be directed to the refinement of the mathematical model of the boiler unit, experimental identification of parameters and more detailed modeling of the traction path. Further work should extend the model toward a more detailed representation of the draft/forced-draft operating mode, validate block parameters using experimental data, and investigate the scheme performance for different fuel types and load ranges.

4. Conclusions

1. The combustion process of the boiler unit was examined as a multivariable control object involving fuel, air, draft, steam-pressure, and oxygen-content channels. The main manipulated variables are fuel flow, air flow, and induced-draft control action, while the primary controlled variables are steam pressure, oxygen content, and furnace negative pressure. The analysis showed that there are significant cross-couplings between the fuel, air, and draft channels. This explains why tuning each control loop independently is not sufficient, especially during load transients.

2. A coordinated control structure was justified, combining fast fuel-air coordination with slower oxygen-based correction. The air-flow setpoint reached its maximum normalized value of 1.0 at approximately 50 s. After the transient period, it settled near 0.82–0.85 by about 120–150 s. The oxygen-trim signal remained relatively small, ranging approximately from −0.03 to +0.04, which confirms that it performs a supervisory function rather than acting as a direct fast-control signal. The key result is the clear separation between fast flow coordination and slow oxygen correction.

3. A simulation model of the automatic control system was developed in MATLAB/Simulink. The model includes the controller, plant dynamics, actuator limits, oxygen-channel inertia, fuel-air

cross-couplings, and a load disturbance. In the steam-pressure loop, the fuel control signal reached its upper limit of 1.0 at around 52–58 s. It then decreased and stabilized near 0.77 by the end of the simulation. This demonstrates that the model takes physically feasible control limits into account.

4. The transient behavior of the system was evaluated under a setpoint change and a load disturbance of 0.1 applied at 160 s. Steam pressure reached a maximum value of about 0.79 with a setpoint of 0.70, corresponding to an overshoot of approximately 13–14% relative to the final setpoint. After the disturbance, steam pressure dropped to around 0.68, but recovered to approximately 0.70 by 220–230 s. Oxygen content decreased from 3.5 to about 3.03 near 85 s, then rose to approximately 3.85 at around 165–170 s. By 250–260 s, it approached the range of 3.55–3.60. The plotted responses show no persistent oscillations. Therefore, the proposed automatic control system maintained stability and restored the main controlled variables after disturbances.

Conflict of interest

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

Financing

The research was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Mykola Tarasenko: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft; ***Petro Kachanov***: Supervision, Validation, Writing – review and editing, Project administration.

References

1. Gilman, G. F. (2010). *Boiler control systems engineering.* Isa. Available at: https://kh.aquaenergyexpo.com/wp-content/uploads/2023/06/boiler-control-system-engineering.pdf
2. Ganapathy, V. (2002). *Industrial boilers and heat recovery steam generators: design, applications, and calculations.* CRC Press. https://doi.org/10.1201/9780203910221
3. Lindsley, D., Grist, J., Parker, D. (2018). *Thermal power plant control and instrumentation: the control of boilers and HRSGs.* Institution of Engineering and Technology, 330. https://doi.org/10.1049/PBPO119E
4. Chernyak, O., Svitiy, I. (2024). To problem of boiler DKVr-10-13 automation in food enterprises' boiler-houses. *Automation of Technological and Business Processes, 16 (2),* 29–38. https://doi.org/10.15673/atbp.v16i2.2839
5. Bhowmick, M., Bera, S. C. (2012). An approach to optimum combustion control using parallel type and cross-limiting type technique. *Journal of Process Control, 22 (1),* 330–337. https://doi.org/10.1016/j.jprocont.2011.06.016
6. Lee, T., Han, E., Moon, U.-C., Lee, K. Y. (2020). Supplementary Control of Air-Fuel Ratio Using Dynamic Matrix Control for Thermal Power Plant Emission. *Energies, 13 (1),* 226. https://doi.org/10.3390/en13010226
7. Kilicaslan, I., Ozdemir, E. (2005). Energy Economy With a Variable Speed Drive in an Oxygen Trim Controlled Boiler House. *Journal of Energy Resources Technology, 127 (1),* 59–65. https://doi.org/10.1115/1.1849227
8. Dukelow, S. G. (1986). *The control of boilers.* ISA. Available at: https://www.scribd.com/document/394874797/Sam-G-Dukelow-the-Control-of-Boilers
9. Seborg, D. E., Edgar, T. F., Mellichamp, D. A., Doyle III, F. J. (2016). *Process dynamics and control.* John Wiley & Sons. Available at: https://elmoukrie.com/wp-content/uploads/2022/06/process-dynamics-and-control-dale-e.-seborg-thomas-f.-edgar-etc.-z-lib.org_.pdf
10. Shinskey, F. G. (1979). *Process control systems.* McGraw-Hill, Inc. Available at: https://skoge.folk.ntnu.no/puublications_others/books/Shinskey-1967-Process%20Control%20Systems.pdf
11. Novikov, P., Shtifzon, O., Bunke, O., Batiuk, S. (2022). Selecting a method for the parametric adaptation of pi-controller in the control systems of boiler assemblies at thermal power stations with supercritical parameters. *Eastern-European Journal of Enterprise Technologies, 2 (2 (116)),* 61–68. https://doi.org/10.15587/1729-4061.2022.254116
12. Astrom, K. J. (1995). *PID controllers: theory, design, and tuning.* The international society of measurement and control. Available at: https://www.ucg.ac.me/skladiste/blog_2146/objava_92847/fajlovi/Astrom.pdf

Petro Kachanov, *Doctor of Technical Sciences, Professor, Department of Automation and Control in Technical Systems, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-7532-5913*

✉***Mykola Tarasenko,*** *PhD Student, Department of Automation and Control in Technical Systems, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, e-mail: mykola.tarasenko@intengin.com.ua, ORCID: https://orcid.org/0000-0001-6877-0173*

✉*Corresponding author*