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Increasing the efficiency of the use of oil fuel in thermal power stations and boilers

Jakhongir Normuminov[1*], *Muhiddin* Tursunov[1], *Abdurauf* Unarov[1] and *Abdullo* Kuchkarov[1]

[1]*Tashkent State Technical University, 100097 Tashkent, Uzbekistan*

Abstract. An organization can achieve good results by properly managing the supply of fuel, ensuring the desired intensity of combustion, and optimizing the volume of the combustion process to promote complete combustion. Additionally, the mixing of fuel with secondary air, provided by combustion devices, is crucial for achieving efficient combustion. Experimental studies conducted on boilers in thermal power plants have demonstrated that heating the secondary air can enhance energy efficiency. This improvement is particularly relevant for fuel oil and gas burning. To optimize the combustion of fuel oil, steam-mechanical nozzles are commonly utilized. These nozzles excel in prolonging the combustion process, leading to more efficient fuel oil burning. When burning gas and fuel oil, a two-stage arrangement of burners in the boiler is more effective than a single-stage configuration, regardless of whether the burners are positioned in opposite directions or in a one-sided frontal arrangement. To mitigate the emission of nitrogen oxides, several measures can be taken. It has been observed that recirculating flue gases from the heat is more effective than solely utilizing flue gas. Additionally, the strategic placement of boilers with furnace gases and the optimization of turning parameters can also contribute to reducing harmful nitrogen oxide emissions.

1. Introduction

Fuel serves numerous purposes beyond transportation. In modern society, a significant portion of fuel is used in industrial production, construction and infrastructure maintenance, heating and cooling systems, and powering information and entertainment technologies. The transition from biomass and primary energy sources to fossil fuels (coal, oil, and natural gas) over the past 250 years has had a profound impact on human experiences of self, time, and place.

Currently, the world is facing its first global energy crisis, which is unparalleled in terms of its scope and complexity. Market pressures existed before Russia's actions in Ukraine, but those actions escalated the situation into a full-blown energy crisis. As the world's largest exporter of fossil fuels, Russia's restrictions on natural gas supplies to Europe, coupled with European sanctions on Russian oil and coal imports, have disrupted a vital artery of global energy trade. All fuel types will be affected, but the gas markets are the epicentre of the crisis, as Russia aims to influence consumers by subjecting them to higher energy bills and supply shortages.

The rise in energy prices is exacerbating food insecurity in many developing economies, with the burden falling heavily on impoverished households that allocate a significant portion of their income to energy and food [1]. Approximately 75 million people who recently gained access to electricity may lose their ability to afford it, leading to a rise in the number of people globally without electricity for the first time in years. Additionally, nearly 100 million people may be forced to rely on wood for cooking, sacrificing cleaner and healthier cooking solutions.

Governments have committed over $500 billion to protect consumers from the immediate impacts of energy shortages and high prices, primarily in developed countries. They are rushing to secure alternative fuel supplies and ensure sufficient gas storage. Short-term measures include increasing oil and coal-fired power generation, extending the lifespan of some nuclear power plants, and expediting the development of renewable energy projects.

As markets rebalance, nuclear-backed renewables will experience steady growth, and the current coal high resulting from the crisis will be temporary. The expansion of renewable electricity generation is outpacing the overall growth in electricity generation, reducing the reliance on fossil fuels. The crisis may temporarily increase the utilization rates

*Corresponding author: Iscmmstiai2022@gmail.com

of existing coal-fired assets but will not lead to increased investment in new ones. Tighter policies, a subdued economic outlook, and higher near-term prices will moderate overall energy demand growth. Future energy demand will primarily come from India, Southeast Asia, Africa, and the Middle East. However, China's energy use, which has been a major driver of global energy trends in recent decades, will slow down until 2030 and eventually stabilize as China transitions toward a more service-oriented economy.

In terms of global oil production, it is estimated that there was a significant decline of 6.6 million barrels per day (Mb/d) over the course of the year. This decline represents the largest fall in post-war history. To understand the supply response and its timing, the year can be divided into three phases.

Phase 1 covers the onset of the global pandemic from December 2019 to April 2020. During this period, global oil consumption plummeted, reaching a low point in April with demand more than 20 Mb/d below pre-COVID-19 levels. This decline was unprecedented in history. However, the initial supply response was insufficient. OPEC was the obvious source of supply that could react quickly, but the key OPEC+ meeting in early March ended in disagreement, resulting in a brief price war and a temporary increase in supply.

As a result, oil inventories accumulated at an unprecedented rate, adding approximately 750 million barrels in just four months. This level of imbalance created severe logistical challenges in terms of storage availability and the ability to rapidly store excess supplies.

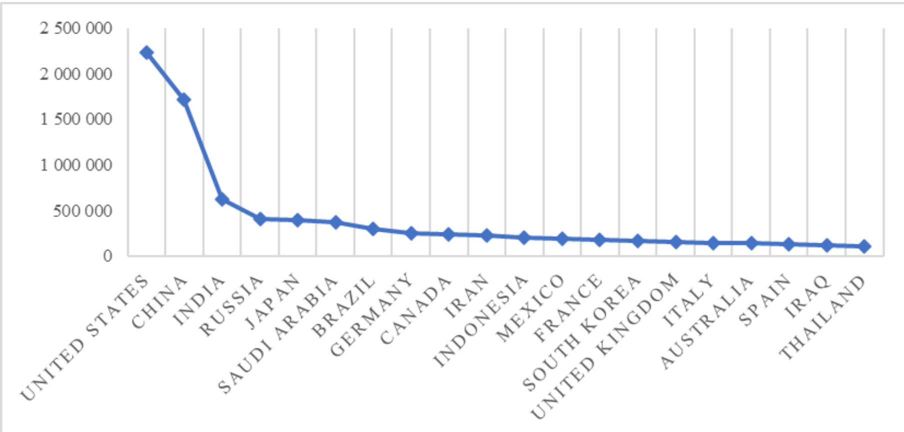

Fig. 1. Carbon dioxide emissions from oil combustion worldwide in 2021, by selected countries**.**

Prices responded accordingly, with Brent reaching a low of below $20/bbl in April. The oil markets made front-page news as US WTI prices turned negative for the first time ever.

During the second phase, from April to August, there was a significant supply response. The main supply reaction came from OPEC+, who agreed to cut oil production by 9.7 Mb/d between May and June, later extended to July. US tight oil production also declined, with a decrease of around 2 Mb/d between March and May.

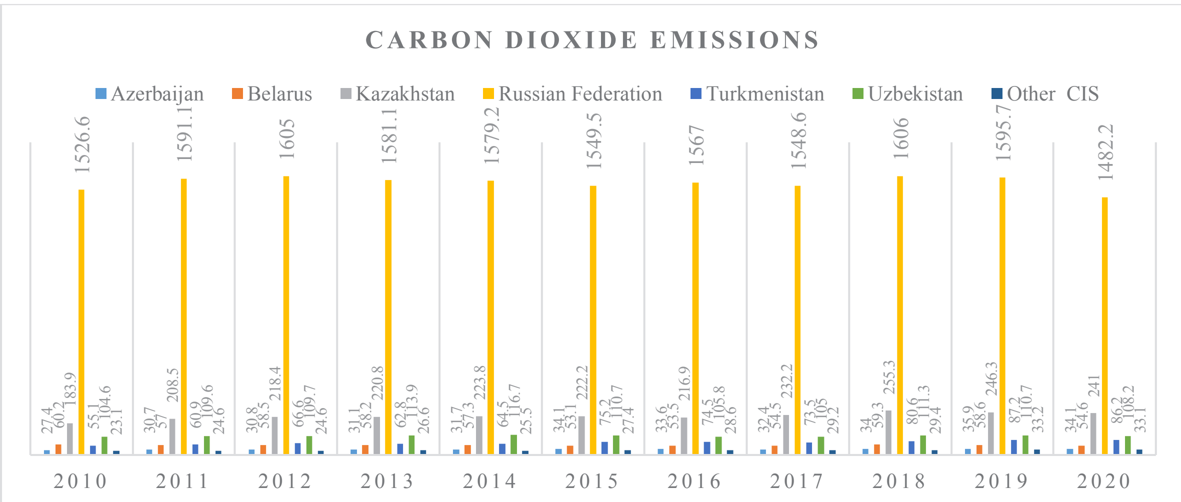

Fig. 2. Carbon dioxide emissions

2. Materials and Methods

The most significant trend in the development of dimensional markets in the oil refining industry is the increasing depth of oil refining and the production of high-quality petroleum products. In 2021, the refining depth is expected to reach 80-85%. As the refining depth deepens, the proportion of straight-run fuel oil used in boiler fuels decreases, while the share of tar and heavy residues from cracking processes increases. Consequently, the quality of heating oil deteriorates.

In 2022, the global demand for crude oil, including biofuels, was approximately 99.57 million barrels per day. It is projected to further increase to around 101.89 million barrels per day in 2023. The decline in demand observed in 2020 was primarily caused by the economic and mobility impacts of the coronavirus pandemic, which led to widespread shutdowns across the world. However, when comparing the daily oil demand of 84.8 million barrels in 2010, it is evident that there has been a clear upward trajectory in demand over the past decade.

The road sector remains the largest consumer of oil worldwide, accounting for over one-third of the global oil demand. This significant demand is primarily driven by the reliance on motor spirits derived from petroleum. According to projections by the Organization of the Petroleum Exporting Countries (OPEC), global oil product demand is expected to reach 109.8 million barrels per day by 2045. Transportation fuels such as gasoline and diesel are anticipated to continue being the most consumed oil products.

The forecast predicts that diesel and gasoil demand will amount to 30.1 million barrels per day in 2045, compared to 27.6 million barrels per day in 2021. Similarly, gasoline demand is projected to reach 27.6 million barrels per day by 2045.

During the normal operation of boiler plants, combustion products are continuously released into the atmosphere, containing substances that have harmful effects on plant, animal, and human life. The combustion of gaseous fuels results in the release of carbon dioxide (CO_2), nitrogen oxides (NOx) such as NO and NO_2, and a small amount of incomplete combustion products such as carbon monoxide (CO) [3].

In 2023, high-sulfur fuel oil grade M100 was burned at TashTPP, resulting in the formation of harmful gaseous products such as sulfur oxides, nitrogen oxides, carbon oxides, vanadium oxides, benzopyrene, and more.

The most effective method for removing CO_2 from flue gases of thermal power plants is chemisorption, which involves using amines as absorbents. Additionally, aqueous solutions of Na_2CO_3, K_2CO_3, NaOH, KOH, $Ca(OH)_2$, and NH_4OH are used as absorbers.

Fuel oil combustion products contain carbon dioxide, nitrogen oxides, sulfurous and sulfuric anhydrides (SO_2 and SO_3), vanadium compounds, carbon monoxide, methane, and particles of sediments that are removed from the heating surface of boiler units during cleaning. Furthermore, during the combustion of various types of fuel, benzo(a)pyrene ($C_{20}H_{12}$), a polycyclic aromatic hydrocarbon, is released into the atmosphere.

To clean gas emissions from boilers and thermal power plants that operate on fuel oil, the ozone-ammonia method is chosen for the absorption of nitrogen oxides and sulfur dioxide. This method involves introducing ozone into the flue gases, which oxidizes sulfur and nitrogen oxides (SO_2 and NO) to form oxides of SO_3, N_2O_2, and N_2O_5, which can be effectively absorbed by water. Industrial water is used as the absorbent in this process. Physical absorption occurs during the cleaning of flue gases from nitrogen oxides and sulfur dioxide.

The design of a packed absorber with two sections and a blind plate between them was calculated for the comprehensive cleaning of flue gases from Tashkent TPP, targeting sulfur dioxide, nitrogen oxides, and carbon dioxide removal. The first section of the packing is dedicated to removing sulfur dioxide and nitrogen oxides, while the second section focuses on removing carbon dioxide. A 15% aqueous solution of monoethanolamide (MEA) was used for capturing carbon dioxide, facilitating the chemisorption process according to the given mechanism.

$$CO_2 + 2RNH_3 + H_2O \rightarrow (RNH_3)_2CO_3 \quad (1)$$

$$CO_2 + (RNH_3)_2CO_3 + H_2O \rightarrow 2RNH_3HCO_3 \quad (2)$$

where R —is the $OHCH_2CH_2$ group

As a result of these reactions, the mass transfer coefficient in the liquid phase increases by the factor of the acceleration coefficient:

$$\gamma = \frac{2(M\sqrt{\theta+1}}{1+\sqrt{1+4(\frac{M\sqrt{\theta}}{R})^2}} \quad (3)$$

where $M = \frac{B_l}{nA_s}, \theta = \frac{D_w}{D_a}, R = \frac{1}{\beta_l}\sqrt{\frac{2}{\alpha+1} r_n B_l^{\beta} D_w A_s^{\alpha-1}}$

where B_l − concentration of the active part of the chemisorbent in the bulk liquids, kmol/m^3; n − stoichiometric coefficient; A_s − concentration of free CO_2 in the solution at the phase boundary, kmol/m^3; D_w − coefficient of molecular diffusion of the chemisorbent, m^2/s; D_a − coefficient of molecular diffusion

of CO_2 in the absorbent, m^2/s; β_l − mass transfer coefficient in the liquid phase; α − reaction order according to A; r_n −forward reaction rate constant; β − reaction order B. The height of the packed bed of the column was determined using the ideal displacement model and the diffusion model of the flow structure.
The packed bed height according to the ideal displacement model has the form

$$H = h_s n_s \quad (4)$$

where h_s − height of transfer units, m; n_s − number of transfer units.
The height of the transfer units was calculated:

$$h_s = \frac{\hat{G}}{\rho_g K_s S_k \alpha_v \psi_a} \quad (5)$$

where $\hat{G} = G\left(1 - \frac{M_a y_n}{M_{sog}}\right)$, kg/s; ρ_g − gas density, kg/m^3; K_s − mass transfer coefficient, m/s; S_k − cross-sectional area of the column, m^2; α_v − specific surface of the packing, m^2/m^3; ψ_a − active surface mass transfer coefficient.
According to the one-parameter diffusion model, the packing layer height was determined from the solution of the system of equations:

$$\begin{cases} W_l \frac{dX}{d\xi} = D_{ml} \frac{d^2X}{d\xi^2} + r_x \\ W_g \frac{dY}{d\xi} = D_{mg} \frac{d^2Y}{d\xi^2} - r_y \end{cases} \quad (6)$$

where D_{ml}, D_{mg} − coefficients of longitudinal mixing in the liquid and gas phases, m^2/s; $r_y = (Y, \xi)$, $r_x = (X, \xi)$ − bulk sources of mass in phases; ξ − longitudinal coordinate (along the height of the layer).
The calculation of a packed absorber for the complex cleaning of flue gases generated by the use of high-sulphury fuel oil grade M100 at gas-oil boilers and at thermal power plants with a flue gas flow rate of less than 25 kg/s.
The results of calculating the packed absorber according to the ideal displacement model and the diffusion model for complex gas cleaning using fuel oil (gas flow rate 7.08 kg/s) are presented in Table 1 [5].
The design of the calculated mass-transfer column for the complex purification of flue gases from nitrogen oxides, sulfur oxides and carbon dioxide has been developed (Fig. 3). The proposed mass transfer apparatus consists of two sections of the nozzle and a "blank" plate between them. Flue gases enter through a side outlet at the bottom of the absorber. The gases pass through the packing section, where they are cleaned from nitrogen oxides and sulfur oxides using technical water as an absorber.

Table 1. Initial data for calculating the absorber

Value	
Mass gas flow	7.08 kg/s
Temperature	55 °C
Pressure	1 atm
Initial concentration of sulfur dioxide	0.003247 mol. d
Initial concentration of nitrogen oxides	0.356 mol. d
Initial concentration of carbon dioxide	0.109 mol. d
Absorbent for absorbing sulfur dioxide and nitrogen oxides Absorbent to absorb carbon dioxide	technical water 15% MEA
Degree of extraction	0.95

Further, the flue gases, bypassing the "blind" plate, pass through the second section of the absorber, where they are cleaned from carbon dioxide absorbed by the monoethanolamide solution. The cleaned flue gases are released from the mass transfer column through the top nozzle. Waste MEA absorbents and industrial water exit the column at low gas velocities through the lower nozzles in the sections. The device operates in film mode, ensuring that the gas flow does not affect the rate of flow of the liquid film down the nozzle and, consequently, the amount of liquid retained in the nozzle. The calculated apparatus provides high cleaning efficiency and relatively small geometric dimensions. Its dimensions and metal consumption are 25-30% less than those of an absorber with Raschig rings. The apparatus operates in film mode at low gas velocities, maintaining consistent liquid flow down the nozzle without gas flow interference.
The calculation of the absorber considered above was also performed with a regular roll nozzle called "Inzhekhim." It was determined that a packing with a rough (bulky) surface provides the best mass transfer characteristics. The height of the sections in the absorber with this nozzle is 16% less compared to the irregular nozzle "Inzhekhim," while maintaining similar hydraulic resistance. Therefore, both irregular and regular packing can be used in the developed absorber (Fig. 3).

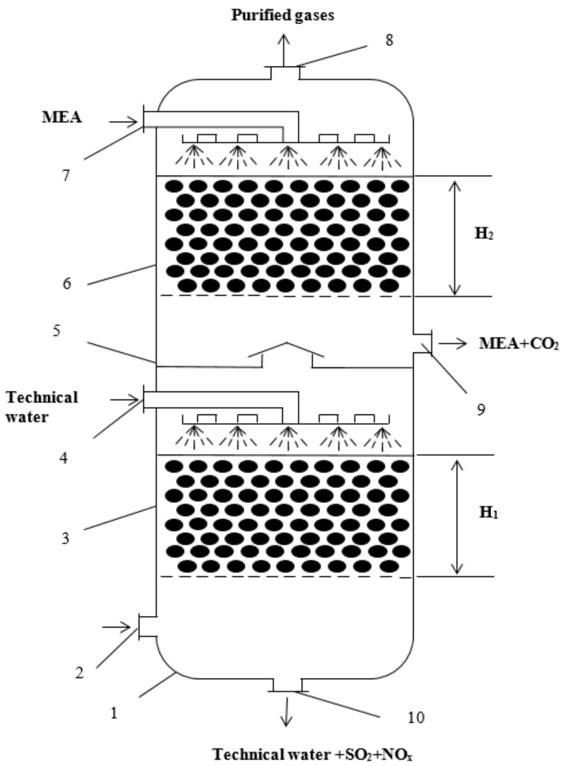

Figure 3. Absorber for complex flue gas cleaning: 1–absorber, 2, 4, 7–inlet pipes, 8, 9, 10–outlet pipes, 3–nozzle section for capturing SO_2 and NO_x with height H_1, 6–nozzle section for capturing CO_2 with height H_2, 5– "blind" plate.

The purified combustion products are directed to the droplet eliminator, where the two-phase flow is separated. They are then heated in the heat exchanger to 80-90 °C before being discharged into the chimney. The absorption solution, separated from the gases and with a pH of 3-4 (due to acid formation), drains by gravity into a container through a water seal in the droplet eliminator. To reduce equipment corrosion, 25% ammonia water is introduced into the container with the collected components. The dosage of ammonia water is adjusted to maintain a pH of 5-6 in the solution.

The resulting solution is continuously fed into the reactor-oxidizer, where sulfites, bisulfites, and nitrites are oxidized to sulfates and nitrates through the bubbling of air. The resulting salt solution, designated as solution 153, is then transferred to the fertilizer drying and granulation unit, where it can be utilized in agriculture as fertilizers [7-8].

As a result of partial neutralization, the solution contains a mixture of salts, including $(NH_4)_2SO_3$, NH_4HSO_3, $(NH_4)_2HSO_4$, NH_4HSO_4, NH_4NO_2, and NH_4NO_3.

3. Results and their Discussion

Film absorbers with weak phase interaction typically exhibit relatively low productivity. Therefore, for the cleaning of large-scale gas emissions in the energy sector, high-speed devices are employed, where the gas velocity can reach 40-50 m/s. In a study, it was demonstrated that a tubular film apparatus operating with a downward concurrent flow at a gas velocity of 30 m/s achieves a gas purification efficiency of up to 90% for SO_2 and NO_2, which falls short of meeting the Maximum Permissible Concentration (MPC) standards for thermal power plants (TPPs) [9-11].

Table 2. Experimental data on the operation parameters of boilers at various steam loads during gas combustion in burners of various designs

Boiler	*Loading D, t/h*	*Air excess coefficient, α*	*Leaving gases temperature t_{og}, °C*	*The NO_x content in flue gases calculated as α=1,4 mg/m^3*	*Efficiency gross η, %*
TGM-94	*500*	*1.04*	*128*	*1.29*	*93.54*

Table 2 presents comparative experimental data on the operational parameters of boilers under different steam loads during gas combustion using burners of various designs and placements within the boiler furnace.
The results of the study indicate that when the temperature of the feed water is maintained through external heat sources, it becomes necessary to activate smoke exhausters for flue gas recirculation in order to sustain the desired overheating temperature of the main and secondary steam. Additionally, when employing external feedwater heating to increase the maximum power output of the power unit, there is a possibility that the feedwater may not reach the required temperature level during nominal operation. To investigate this, the TGM-94 steam boiler was studied using the described mathematical model, considering a variable feed water temperature at the inlet. Two modes were calculated:

1. In the first mode, fuel consumption remains constant at the nominal level.
2. In the second mode, the nominal steam capacity (500 t/h) is maintained by adjusting the fuel oil consumption.

In the operating mode of the boiler with a reduced feed water temperature at the inlet and constant fuel consumption, an increase in efficiency of 0.3% was observed. However, the steam production decreased from 500 t/h to 467 t/h when the feed water temperature changed from 235°C to 175°C. This decrease in steam production by 48 t/h would have a significant impact on the power output of the steam turbine. Under these conditions, the injection for cooling the superheated steam increases substantially, while the temperature of the secondary steam remains practically unchanged. The most significant findings of the research are depicted in figures 4 and 5.

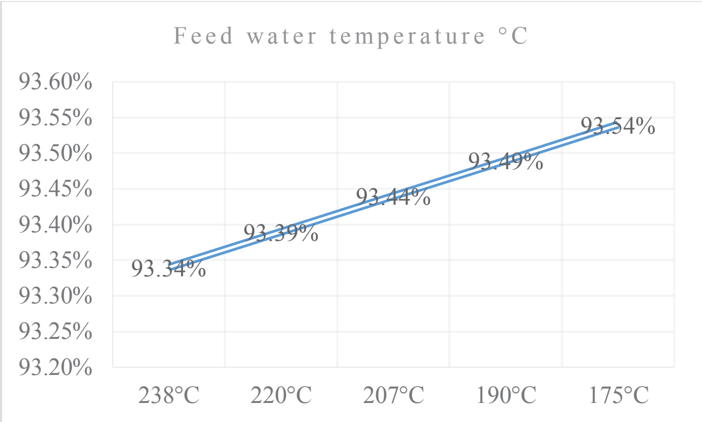

Fig. 4. Dependence of boiler efficiency on feed temperature

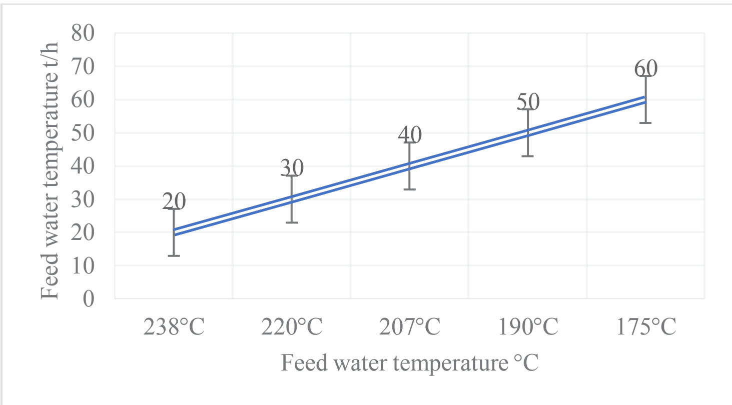

Fig. 5. The dependence of the water flow water rate for injection to cool the hot steam from the feed water temperature

At a feed water temperature of 160 ºC, the temperature of the superheated steam exceeds the permissible limits, as the capacity for installing internal condensers, which generate condensate for injection, has been exhausted. Additionally, an additional evaluation of the temperature condition of the metal on the heat exchange surfaces is necessary to ensure the reliability of their operation under these circumstances.

4. Conclusion

The utilization of flue gas recirculation to reduce nitrogen oxide emissions in boiler exhaust gases has a significant impact on burner placement and optimization of the turning parameter. Implementing a flue gas recirculation system, along with a smoke exhauster, to minimize nitrogen oxide emissions from boiler flue gases yields greater results compared to optimizing the burner layout and twist parameter [12-13].

In this study, a mathematical model of the TGM-94 steam boiler was developed, alongside a K-150-130 steam turbine plant. The mathematical model was validated using real data obtained during the operation of the power unit within the Tashkent TPP. The coolant temperature along both the steam and gas paths demonstrated sufficient convergence. However, notable differences in temperature values were observed, particularly in the feed water after the first stage of the economizer, flue gases, and air at the furnace inlet. The maximum variation between the calculations and experiments was 8 ºC. These discrepancies could be attributed to measurement errors and limitations in the mathematical modeling methods.

The TGM-94 boiler's performance was examined under variable loads while maintaining a constant feed water temperature of 238 ºC, which corresponds to its nominal value. This article emphasizes the necessity of conducting additional calculations for the steam boiler whenever modifications are made to the regenerative heating system of the steam turbine plant. These calculations ensure the assessment of the boiler's performance and efficiency under new operating conditions [14-15].

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