Transformation of Radiation–Convective Heat Transfer and Thermomechanical State of Industrial Steam Generators under Furnace-Space Ballasting with Carbon Dioxide from Biogas

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Abstract. The purpose of this study is to provide a scientific substantiation of the mechanisms governing changes in the structure of local heat absorption and the kinetics of pollutant formation when natural gas is replaced by biogenic gas mixtures ballasted with carbon dioxide. To achieve this objective, the following tasks were accomplished: numerical simulation of three-dimensional combustion processes was performed, and an accurate assessment of the thermomechanical state of critical boiler unit components was conducted. The integrated numerical approach combines Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) methods over an extended load range (40–100% of nominal capacity). The scientific novelty of the results lies in the identification of the physical effect of radiation heat transfer intensification within the furnace volume due to an increase in the partial pressure of triatomic gases (CO_2), which compensates for the reduction in the adiabatic flame temperature of biogas. It has been theoretically demonstrated that an increase in the volumetric flow rate and emissivity of combustion products leads to a redistribution of thermal load along the boiler circuit, causing a stable increase in temperature within the convective pass by 20–25 °C. This effect ensures that the flue gas temperature remains above the dew point, thereby eliminating the risk of low-temperature corrosion of heating surfaces under deep load-following operating conditions. The practical significance of the study lies in establishing the regularities of local heat flux homogenization, which reduces temperature gradients and the amplitude of peak thermomechanical stresses in the metal of waterwall tubes and drums by 15–20%. The obtained results provide a scientific basis for predicting the service life and thermal reliability of pressure-retaining components in the context of energy sector decarbonization.
Keywords: biogenic gas mixtures, computational fluid dynamics (CFD), thermostructural analysis (FEA), radiative heat transfer, deoxification, decarbonization.

DOI: https://doi.org/10.52254/1857-0070.2026.3-71.02
UDC: 621.18

Transformarea transferului de căldură prin radiație-convecție și starea termomecanică a generatoarelor industriale de abur sub balastare în spațiul cuptorului cu dioxid de carbon din biogaz

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Rezumat. Scopul studiului este de a oferi o fundamentare științifică a mecanismelor care guvernează modificările structurii absorbției locale de căldură și cinetica formării poluanților atunci când gazul natural este înlocuit cu amestecuri de gaze biogene balastate cu dioxid de carbon. Pentru a atinge acest obiectiv, au fost realizate următoarele sarcini: s-a efectuat o simulare numerică a proceselor tridimensionale de ardere și s-a realizat o evaluare precisă a stării termomecanice a componentelor critice ale unității cazanului. Abordarea numerică integrată combină metodele de hidrodinamică computațională (CFD) și analiza cu elemente finite (FEA) pe un interval extins de sarcină (40–100 % din capacitatea nominală). Noutatea științifică a rezultatelor constă în identificarea efectului fizic al intensificării transferului de căldură prin radiație în volumul cuptorului, datorită creșterii presiunii parțiale a gazelor triatomice (CO_2), care compensează reducerea temperaturii flăcării adiabatice a biogazului. S-a demonstrat teoretic că o creștere a debitului volumetric și a capacității de emisie a produselor de ardere conduce la o redistribuire a sarcinii termice de-a lungul circuitului cazanului, provocând o creștere stabilă a temperaturii în trecerea convectivă cu 20–25 °C. Acest efect asigură menținerea temperaturii gazelor de ardere peste punctul de rouă, eliminând astfel riscul coroziunii la temperatură scăzută a suprafețelor de încălzire în condiții de funcționare sub sarcină intensă. Semnificația practică a studiului constă în stabilirea regularităților omogenizării fluxului termic local, care reduce gradienții de temperatură și amplitudinea solicitărilor termomecanice de vârf în metalul tuburilor și tamburelor peretelui de apă cu 15–20 %. Rezultatele obținute oferă o bază științifică pentru prezicerea duratei de viață și a fiabilității termice a componentelor care lucrează sub presiune, în contextul decarbonizării sectorului energetic.

Cuvinte-cheie: amestecuri de gaze biogene, dinamica fluidelor computațională (CFD), analiză termostructurală (FEA), transfer radiativ de căldură, dezoxificare, decarbonizare.

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Аннотация. Целью данного исследования является научное обоснование механизмов изменения структуры локального тепловосприятия и кинетики образования загрязняющих веществ при замене природного газа биогенными газовыми смесями, балластированными диоксидом углерода. Для достижения поставленной цели были решены следующие задачи: выполнено численное моделирование трехмерных процессов горения и проведена точная оценка термонапряженного состояния критических элементов котельного агрегата. Комплексный численный подход объединяет методы вычислительной гидрогазодинамики (CFD) и метод конечных элементов (FEA) в расширенном диапазоне нагрузок (40...100% от номинальной). Научная новизна результатов заключается в выявлении физического эффекта интенсификации радиационного теплообмена в топочном объеме за счет увеличения парциального давления трехатомных газов (CO_2), что компенсирует снижение адиабатической температуры пламени биогаза. Теоретически доказано, что увеличение объемного расхода и излучательной способности продуктов сгорания приводит к перераспределению тепловой нагрузки по контуру котла, вызывая стабильный рост температуры в конвективной шахте на 20...25 °C. Этот эффект гарантирует превышение температуры уходящих газов над точкой росы, полностью исключая риск низкотемпературной коррозии поверхностей нагрева в условиях глубокого маневрирования. Практическая ценность работы заключается в установлении закономерностей гомогенизации локальных тепловых потоков, что снижает температурные градиенты и амплитуду пиковых термомеханических напряжений в металле экранных труб и барабанов на 15–20%. Полученные результаты обеспечивают научную базу для прогнозирования срока службы и тепловой надежности элементов, работающих под давлением, в контексте декарбонизации энергетики.

***Ключевые слова*:** биогенные газовые смеси, вычислительная гидродинамика (CFD), термоструктурный анализ (FEA), радиационный теплообмен, деноксификация, декарбонизация.

INTRODUCTION

The dynamic growth of the share of biogas in Ukraine's energy balance is driven by the pursuit of energy independence and compliance with European Union environmental standards. This fuel, primarily composed of methane and carbon dioxide, represents a promising alternative to conventional hydrocarbons. Given consistent state policy, the share of renewable resources may reach 91% by 2050. Research efforts in this area are focused on the specific features of biogas utilization in thermal power installations, where differences in the properties of the working media (up to 6%) require refinement of conventional thermal engineering calculations to ensure efficient boiler operation [1].

The use of biogas as an alternative energy carrier is a logical step within the framework of the decarbonization strategy. Practical tests conducted on a hot-water boiler using a fuel mixture of 76% CH_4 and 24% CO_2 demonstrated the potential to reduce NO_x emissions to 63–76 mg/Nm³. This emission level complies with European environmental requirements for industrial installations with a capacity exceeding 1 MW, making biogas an effective means of improving the environmental performance of aging boiler units [2].

The main components of biogas are methane and carbon dioxide; however, their proportions depend significantly on the characteristics of the feedstock, fermentation duration, and digestion technology. The volumetric fraction of methane typically ranges from 45% to 80%, whereas the carbon dioxide content varies from 20% to 55%. Additional impurities, such as ammonia, hydrogen, and hydrogen sulfide, do not exceed 3% in total. For standard calculations, a composition of 70% CH_4 and 30% CO_2 is usually assumed. Compared with natural gas, biogas has a lower calorific value (approximately 25 MJ/m³ versus 35 MJ/m³). This difference necessitates an increase in volumetric fuel supply by at least 57% to maintain the same thermal output of the unit. Such an increase in fuel consumption, caused by the high level of ballast components, raises the issue of flame stability. In addition to its effect on calorific value and density, a significant CO_2 content reduces the flame propagation velocity to 15–25 cm/s (compared with 38 cm/s for methane), creating a risk of flame lift-off and necessitating special stabilization measures [3].

Biogas is produced through the anaerobic fermentation of organic feedstock under the action of a consortium of hydrolytic, acid-forming, and methanogenic microorganisms. Depending on operating conditions, the methane content of such fuel ranges from 50% to 87%, while the carbon dioxide concentration varies from 13% to 50%. The successful integration of agro-industrial waste into the fuel balance of countries such as Germany and Denmark demonstrates the strategic importance of this approach. However, the adaptation of energy systems to biogas requires modifications to established engineering practices.

In particular, study [4] demonstrated that the difference in the thermophysical properties of biogas combustion products compared with those of natural gas reaches 6%. Neglecting this factor in thermal calculations leads to errors in determining flue gas temperature and to an unjustified increase in fuel consumption.

Particular attention in current research is devoted to suppressing the formation of nitrogen oxides (NO_x). Using Soviet-era steam boiler units as an example, the authors of [4] demonstrated the effectiveness of steam injection into the active flame zone, achieving a 30% reduction in NO_x emissions while maintaining thermal efficiency. At the same time, the integration of flue gas recirculation (FGR) systems (with a recirculation ratio of $r = 17…30\%$) makes it possible to increase NO_x reduction efficiency to 75%.

However, biogas requires purification and upgrading to ensure its effective use as a fuel or for injection into the natural gas grid. Biogas upgrading not only increases its calorific value but also reduces the risk of corrosion. In this context, the importance of biogas is emphasized with regard to its origin, properties, and applications. Furthermore, various physicochemical and biological methods commonly used for biogas upgrading have been reviewed, with particular attention to their operational advantages and limitations.

The authors of [5] presented various strategies for controlling specific impurities present in biogas, including CO_2, siloxanes, H_2S, and other trace compounds. Study [6] provides a review of modern biogas upgrading and purification technologies aimed at increasing methane content and removing CO_2 and H_2S. The effectiveness of various technologies, including the use of natural adsorbents, biological treatment methods, and mathematical modeling of biogas purification processes, was analyzed. At present, technologies for upgrading biogas to biomethane quality are actively being developed.

In [7], conventional physicochemical methods for removing impurities (CO_2, H_2S, and other gases) as well as emerging biological technologies based on methanation and the use of microalgae were analyzed. The advantages, disadvantages, and prospects of implementing various methods were considered, and the main technological barriers and directions for further development of efficient and environmentally safe biogas upgrading systems were identified.

Fluctuations in fuel density induce changes in its flow characteristics when passing through burner orifices. As a consequence, gas discharge velocities must be reassessed, which fundamentally alters the conditions of turbulent mixing with the oxidizer. Such aerodynamic changes affect the completeness of combustion and the thermal output of the unit.

The influence of carbon dioxide should be highlighted separately, as its presence contributes to a reduction in flame temperature potential, which is an effective means of suppressing NO_x formation [3]. The authors of [4] determined that CO_2 ballasting leads to suppression of the combustion intensity of methane–air mixtures. The analysis of the data confirms that the initiation of fuel dilution with CO_2 is accompanied by a monotonic decrease in laminar burning velocity [4].

Within the framework of study [8], an assumption is made regarding the absence of nitrogen in the biogas mixture, where the component concentrations are calculated as $CO_2 = 100\% – CH_4$. Thus, the analysis is focused on the dynamics of properties depending on the fractions of methane and carbon dioxide. It has been established that an increase in CO_2 content leads to a monotonic decrease in thermal diffusivity. This phenomenon is explained by the high heat capacity of carbon dioxide, which inhibits the rate of heat transfer in the working medium. In addition, as pressure increases from 1 to 5 bar, an almost fivefold decrease in thermal diffusivity is observed, which is a consequence of significant densification of the fuel mixture.

In [9], it is concluded that flame radiation intensity correlates with CO_2 concentration: as the carbon dioxide fraction increases, a reduction in flame luminosity is observed. In this case, combustion dynamics transition from unstable cyclic regimes to a critical state close to lean flame extinction. The addition of carbon dioxide inhibits chemical reactions, leading to a visual weakening of the flame front and its longitudinal elongation in the direction of the flue gas duct [10, 11].

Injection of carbon dioxide into biogas mixtures causes a decrease in the temperature of combustion products, which serves as an effective means of suppressing NO_x formation. However, the reduction in adiabatic flame temperature inhibits chemical reaction rates, resulting in an increase in carbon monoxide (CO) concentration. Although direct CO_2 emissions from biogas combustion are higher than those from natural gas, according to the life-cycle concept, this fuel remains carbon-neutral, since the released carbon was previously absorbed by biomass [12].

According to the results of [12], the increase in CO_2 emissions may reach 100% compared with methane; however, the overall greenhouse gas balance does not deteriorate. Moreover, the utilization of organic waste through biogas production prevents uncontrolled methane emissions from landfills, whose greenhouse potential significantly exceeds that of carbon dioxide.

Studies [13] conducted on opposed-flow burners confirm that CO_2 exerts both thermal and chemical effects on flame structure. In particular, dilution of the fuel with carbon dioxide to a level of 0.4 reduces the concentrations of O and OH radicals, which enables a decrease in NO_x emissions from 52 to 38 mg/m³.

For the efficient utilization of biogas in boiler units in Ukraine, bottom-fired burner systems have been implemented (nominal fuel flow rate – 318 m³/h) [14]. These installations demonstrate stable operation over a wide load range (44–100% of nominal capacity) with biogas consumption in the range of 426–954 m³/h. At the same time, pollutant concentrations remain minimal (CO $\approx$ 46–50 mg/m³, NO_x $\approx$ 42–54 mg/m³), while the annual economic effect reaches fuel savings of 2–3 million m³ per boiler.

In [15], the use of biogas for reducing nitrogen oxide (NO_x) emissions during fuel combustion in industrial boilers was investigated using CFD modeling. Through numerical simulation, the influence of biogas composition, its dilution ratio, and injector arrangement on NO_x reduction efficiency was analyzed. Optimal biogas injection conditions were determined, ensuring improved flue gas cleaning efficiency and reduced losses due to incomplete combustion.

Owing to the implementation of third-generation slot-type bottom burners and double-screen radiation systems, it has become possible to achieve NO_x emission levels fully compliant with European Union standards for medium-capacity boiler installations.

A current development trend in the industry is the transition to biogenic fuels. Based on analytical forecasts [16], the share of the renewable sector in Ukraine's energy system may increase to 91% by 2050. In this context, biogas (CH_4 – 50…87%, CO_2 – 13…50%) serves as a strategic substitute for conventional natural gas.

However, the engineering adaptation of power boilers to biogas requires accounting for a 6% discrepancy in the properties of combustion products compared with the reference fuel, which necessitates refinement of classical thermal calculation methods.

In study [17], the effect of CO_2 ballasting on the emission of incomplete methane oxidation products was analyzed using a vortex combustion chamber as an example. The authors found that, at a fixed fuel–air equivalence ratio, the addition of carbon dioxide critically deteriorates combustion completeness.

Of particular interest is the nature of emission changes under the diffusion regime, where an initial decrease in CO emissions was observed at moderate mixture enrichment up to Φ = 0.70, followed by an increase at Φ values above 0.75.

According to experimental results from co-firing systems in 300 MW tangential furnaces [18], biogas dosing provides a consistent reduction in nitrogen oxide emissions. The most pronounced environmental benefit at a constant fuel substitution level is observed when combusting biogas derived from wood sawdust. At the same time, adjustment of burner tilt angle to –15° leads to an increase in NO emissions.

In boiler installations with a bubbling fluidized bed, the most effective method of biogas integration is its injection through the first tier of secondary air nozzles, which significantly improves combustion stability compared with the standard injection scheme [19].

According to the results presented in [20], the use of slot-type bottom burners for natural gas combustion ensures a low level of CO emissions within 10 mg/Nm³ (at 3% O_2 content). In the case of switching to biogas with a 50% carbon dioxide concentration, a tenfold increase in carbon monoxide content in the combustion products is observed.

However, since the resulting concentration does not exceed the limit of 100 mg/Nm³, such operating conditions fully comply with current environmental regulations.

Exergy balance analysis of oxy-biogas combustion in adiabatic chambers [21] indicates a reduction in the total specific exergy (chemical and thermomechanical) of flue gases with increasing CO_2 fraction. In particular, when the carbon dioxide concentration increases from 10% to 40%, exergy losses due to incomplete oxidation rise from 5,8% to 13,8%.

Nevertheless, the use of flue gas recirculation (FGR) technology enables the implementation of MILD combustion regimes for mixtures with a 60/40 composition, which homogenizes temperature fields and reduces thermal stresses in structural components [23].

The results of numerical simulation studies [24] confirm that thermal non-uniformity induced by burner design specifics promotes low-cycle fatigue, which under current conditions may limit boiler drum service life to 15 years.

Theoretical analysis of aerodynamics and heat transfer in furnaces performed using ANSYS CFD software packages [25–27] is aimed at the implementation of high-accuracy DNS models. Despite progress in this field, adequate reproduction of chain combustion mechanisms in large-scale volumes remains a challenging computational problem [28].

Experimental and theoretical data [29, 30] indicate a high efficiency of O_2/H_2O operating regimes, providing an increase in heat flux uniformity of up to 129.9%, which is critically important for the reliable operation of waterwall tubes.

The systematization of accumulated scientific knowledge confirms the role of biogas as an important factor in reducing the carbon footprint of the energy sector. At the same time, the complexity of biogas combustion processes leaves room for scientific debate, as many applied aspects of this problem require further detailed clarification and experimental validation.

Alongside the operational advantages of introducing biogenic fuels, techno-economic analysis of alternative utilization pathways is also of significant importance.

In [31], the economic efficiency of integrating biogas into district heating systems, standalone power plants, and the transport sector was investigated. Based on a comparative analysis of different fuel utilization scenarios, relevant development pathways were identified, taking into account a set of technical, financial, and market factors. It was established that cogeneration of electricity demonstrates the highest economic attractiveness, whereas conversion of existing boiler units to biogas is characterized by lower capital intensity and higher technological accessibility for practical implementation.

The transition to biogas is accompanied by risks of flame instability due to the specific fuel composition, where a high carbon dioxide fraction limits combustion velocity and adiabatic flame temperature. This requires the development of burners with enhanced stabilization capability. The main advantage of this technology lies in the environmental improvement of energy generation through suppression of NO_x formation. Successful integration of biogas technologies is possible provided that proper tuning of mixing aerodynamics and adaptation of fuel supply to variations in methane concentration (45…70%) are ensured.

Despite technical challenges associated with its lower calorific value, biogas is a promising carbon-neutral fuel requiring optimization of afterburning processes to achieve target energy efficiency.

Based on the analysis of existing scientific works, the authors formulated a scientific problem consisting in the lack of a comprehensive understanding of the relationship between changes in the radiative properties of a multicomponent flame and the unsteady thermomechanical state of pressure-bearing heating surfaces.

To address this problem, the objective of the study is defined as follows:

- Establishing the regularities of the influence of fuel ballasting with carbon dioxide (CO_2) on the change in the ratio between radiative and convective heat transfer in the furnace spaces of industrial steam generators.
- Determining the kinetic and aerodynamic factors of suppression of thermal NO_x formation via the Zeldovich mechanism under conditions of deconcentration of the flame thermal core in ballasted mixtures.
- Mathematical modeling and assessment of the three-dimensional thermomechanical state of waterwall systems and drum-separators to identify zones of extreme stress localization under variable thermal loads.

Achieving the stated objective will make it possible to address the problem of modernizing the existing fleet of boiler units for their transition to renewable energy sources in a comprehensive manner.

METHODS

In the present study, biogenic gas parameters were used, where the methane fraction is 67.76% and carbon dioxide is 31%. The specifics of modeling in ANSYS Fluent are determined by the need to account for the influence of CO_2 on the thermal and emission characteristics of the flame.

The Species Transport model was used to solve the species transport equations and to evaluate NO_x formation.

Since swirl burners are analyzed in this work, the Realizable k-ε turbulence model was selected to correctly describe the aerodynamics. For the treatment of turbulence–chemistry interaction, the Eddy-Dissipation Concept (EDC) model was implemented, enabling high computational accuracy at acceptable computational cost [21].

The flow of a multicomponent medium is described by the continuity equation and the Navier–Stokes equation.

Energy transport in the combustion zone accounts for convection, thermal conduction, species diffusion, and heat release due to chemical reactions [26]:

$$\nabla\left(u(\rho E + p)\right) = \nabla\left(\lambda_{eff}\nabla T - \sum h_j J_j + \left(\overline{\overline{\tau_{eff}}} u\right)\right) + S_h, \quad (1)$$

where $\nabla\left(u(\rho E + p)\right)$ – the energy flux transported by macroscopic gas motion with velocity u; $\lambda_{eff}\nabla T$ – describes heat transfer due to the temperature gradient $\sum h_j J_j$ – describes heat transfer due to diffusion of chemical species (components j). Each component has its own specific enthalpy h_j. In the biogas combustion zone, this is particularly important, since active diffusion of fuel components (CH_4, H_2) into the reaction zone is accompanied by significant energy transport; $\left(\overline{\overline{\tau_{eff}}} u\right)$ – describes the conversion of the kinetic energy of gas motion into heat due to viscous friction. In boilers, this term is usually negligible but is included for completeness of the mathematical model [26].

The heat source (S_h) is a chemical source [26]. It is calculated as follows:

$$S_h = -\sum_j \frac{h_j^0}{M_j} R_J \quad (2)$$

where h_j^0 – enthalpy of formation of the component; R_j – its rate of production or consumption in the chemical reaction. This term accounts for the lower heating value of biogas. Since biogas contains 31% CO_2, the heat release density Sh in this case is lower than for pure methane.

The rate of production or consumption of component j in the energy equation is defined by the following expression:

$$R_j = \frac{\rho\left(\gamma^*\right)^2}{\tau^*\left(1-\left(\gamma^*\right)^3\right)}\left(Y_j^* - Y_j\right), \quad (4)$$

where ρ is the mixture density; Y_j^* – is the mass fraction of the component after passing through the reaction in the “fine structure” (calculated using the Arrhenius law); Yj is the current mass fraction of the component in the surrounding medium.

To close the turbulence equations in zones of intense burner swirl, the Realizable k-□ model was selected. Radiative heat transfer, whose role increases during biogas operation due to the high content of triatomic gases, was modeled using the Discrete Ordinates (DO) method. This model enables the integration of radiation calculations into a unified system of equations for media with arbitrary optical thickness.

Modeling of emission characteristics (NO_x) was performed accounting for both thermal and prompt components using extended reaction schemes. The ballast components of biogas (CO_2, N_2) and fuel oxygen content were considered in the calculation of adiabatic flame temperature and air consumption. The interaction between turbulence and chemical reactions was described using the Finite-Rate/Eddy-Dissipation model.

The computational domain containing a jet-slot stabilizer (Fig. 1) was discretized using a hybrid mesh. Near-wall regions were refined using structured hexahedral elements, while the remaining domain was filled with tetrahedral elements. The quality metrics of the finite elements (aspect ratio, orthogonal skewness) are within acceptable limits. The computational mesh density was optimized to the constraints of the ANSYS Student license, ensuring the required accuracy without excessive computational cost.

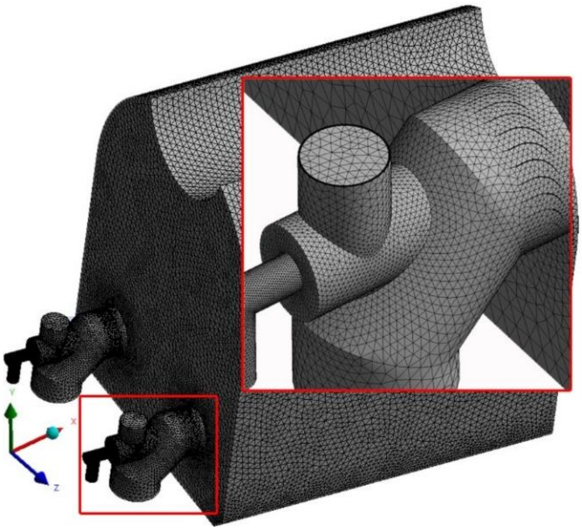


Fig. 1. Finite element mesh used for the discretization of the furnace space of the hot-water boiler.

For modeling combustion processes in the power boiler (Fig. 2), a hybrid finite-element model was constructed, in which a structured hexahedral mesh is combined with a tetrahedral mesh in the burner swirl regions.

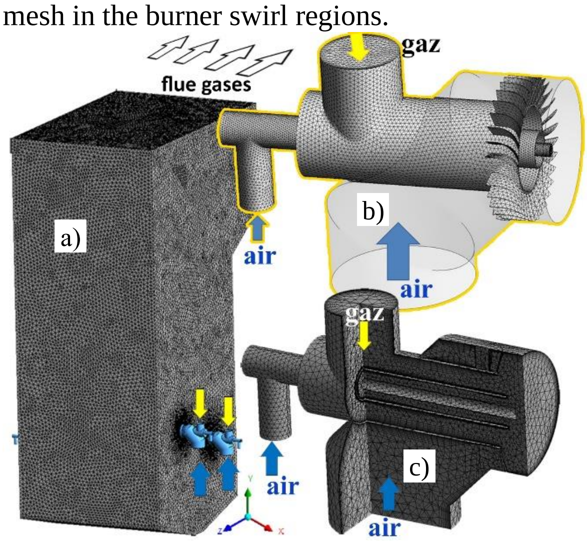


Fig. 2. Finite element mesh of the power boiler (a), detailed view of the burner mesh (b), and longitudinal section of the burner used in the model (c).

To improve accuracy in regions of chemical reactions, the Fine Relevance Center and local Sizing parameters were applied. Correct representation of heat transfer at the furnace walls was achieved through the generation of prismatic layers (Inflation). A grid independence study (Grid Convergence Study), performed by comparing results obtained on meshes of different densities, demonstrated the invariance of integral characteristics (temperature and NO_x emissions) with respect to further mesh refinement.

This confirms the reliability of the computational algorithm within the hardware and software limitations of the ANSYS Academic version, allowing the model to be used for predicting transient operating regimes of the boiler.

To ensure the uniqueness and reproducibility of the numerical solution of the Navier-Stokes and energy transport equations, the following boundary conditions were specified:

1. Fuel inlet (Fuel Inlet): For both computational configurations (natural gas and biogas), a «Mass Flow Inlet» boundary condition was used. The physicochemical properties of the media were defined in terms of mass fractions of components. For natural gas, a simplified model (100% CH_4) was assumed with a lower heating value of 35,8 MJ/Nm^3. For the biogas mixture, the lower heating value was 21,5 MJ/Nm^3. The biogas mass flow rate was recalculated to ensure preservation of the nominal thermal power of the furnace chamber. The inlet temperature of the fuel mixture was set to 313 K, accounting for preheating.

2. Air inlet (Air Inlet): A «Mass Flow Inlet» condition was specified. The excess air ratio (α) was assumed constant for both fuel regimes and equal to 1,05. The inlet temperature of the combustion air at the burner entry was 423 K (150 °C). The air mass flow rate for the biogas case was adjusted according to the stoichiometric ratio of the components to ensure the same excess oxidizer coefficient.

3. Furnace walls (Walls): A «Wall» condition was applied to the waterwall tube surfaces. The thermal regime was defined by a fixed wall temperature (523 K/250 °C), corresponding to the saturation temperature at the boiler drum operating pressure of 3,9 MPa.

4. Combustion products outlet (Pressure Outlet): At the furnace outlet cross-section (at the plane of the pendant superheater bundle), a «Pressure Outlet» condition was specified with a gauge pressure of 0 Pa. To stabilize numerical convergence and prevent oscillations under local backflow conditions, the backflow temperature was set in the range 1200…1400 K (927…1127 °C).

RESULTS AND DISCUSSION

The results of modeling the temperature regime in the longitudinal section of the hot-water boiler furnace are shown in Fig. 4. Comparison of temperature fields illustrates the transformation of furnace processes depending on the fuel type.

Thus, during natural gas combustion (Fig. 3a), a stable flame is formed with localization of the temperature maximum in the center of the combustion chamber. Peak values in the core (1650…1800 °C) result in high radiative heat transfer intensity; however, they also promote intensive formation of thermal NO_x.

The transition to biogas fuel (Fig. 3b) leads to a restructuring of the flame due to the ballast effect of CO_2. A deconcentration of the temperature core and a reduction in maximum temperatures by 100…150 °C are observed. This is consistent with the data in [27] regarding NO_x reduction in the combustion process due to thermal inhibition.

The increased flame reach in biogas combustion is explained by the higher fuel flow rate required to maintain the specified power output, which shifts the thermal load toward the rear wall. According to [27], such changes require refinement of the heat transfer efficiency coefficients of heating surfaces.

Fig. 4 presents the results of modeling local nitrogen oxide (NO_x) concentrations. The visualization confirms that during methane combustion (Fig. 4a), NO_x generation zones coincide with regions of maximum temperature, demonstrating the predominance of the thermal mechanism. In contrast, the use of biogas (Fig. 4b) leads to a significant dispersion of toxic species concentration zones and an overall reduction in emissions.

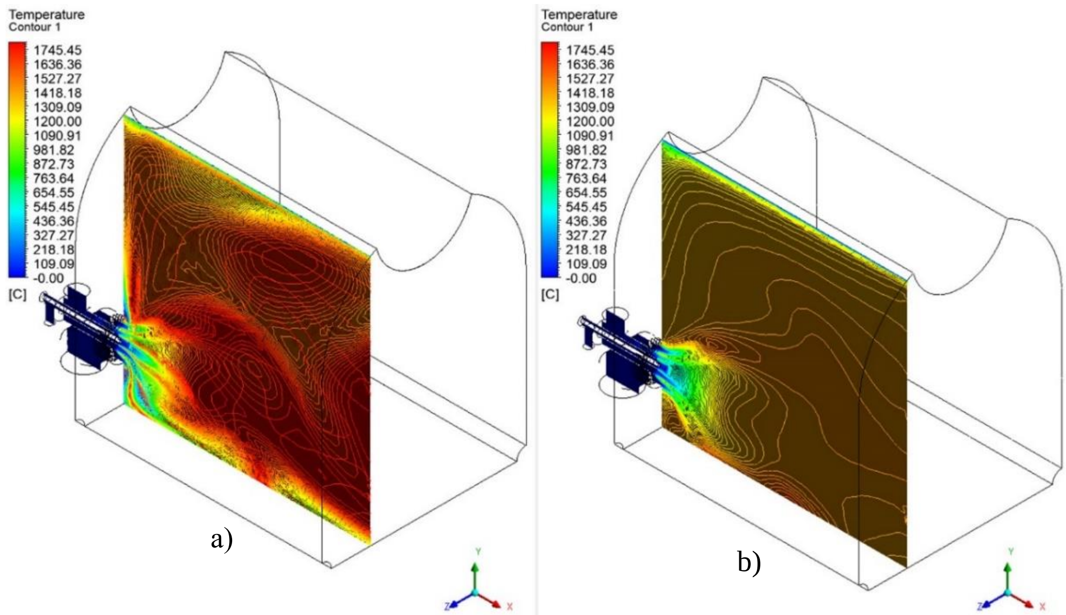


Fig. 3. Temperature distribution in the cross-section of a hot-water boiler furnace during combustion of natural gas (a) and biogas (b).

The presence of carbon dioxide (CO_2) in the structure of biogas acts as an inert ballast, causing a decrease in the average flame temperature level and a smearing of the concentration fields of active reactants. This leads to a significant narrowing of the regions of active formation of nitrogen compounds.

The presented visualization results correlate with practical findings in [27], confirming the ability of energy units to achieve European environmental performance standards without investments in expensive selective gas cleaning equipment.

Analysis of Fig. 4b indicates an elongation of the NO_x formation zone along the furnace space compared with a methane flame. Such a transformation is caused by an increase in volumetric fuel supply and the corresponding modification of the kinetic stages of the process. Nevertheless, despite the expansion of the reaction zone, the integral NO_x levels remain significantly lower than those characteristic of natural gas combustion. Therefore, the conversion of hot-water boilers to biogenic fuel represents an effective denitrification strategy that minimizes anthropogenic environmental impact.

The analysis of local heat absorption of waterwall surfaces (Fig. 5) demonstrates that the use of biogas (Fig. 5a) provides a higher homogeneity of heat load distribution. Although the maximum heat flux values in this case are lower than those for natural gas (Fig. 5), the significant concentration of triatomic combustion products (CO_2) enhances the radiative component of heat transfer.

Thus, while under nominal load with natural gas there is a risk of thermal overstress of tubes due to high local heat intensity, biogenic fuel ensures a more moderate thermal operating regime for the metal. With a reduction in boiler load, a linear degradation of heat fluxes is observed, which correlates with an overall decrease in the temperature potential in the furnace.

The study of the operating characteristics of the boiler confirmed that biogas transforms the combustion structure compared with high-calorific natural gas.

Fig. 6 demonstrates the “smearing” of the high-temperature flame core during the transition to biofuel. Due to CO_2 ballasting of the mixture, a reduction in peak temperatures in the active oxidation zone by 100–150 °C is observed. This moderates the thermal operating conditions of the waterwall surfaces and reduces the risk of local overheating.

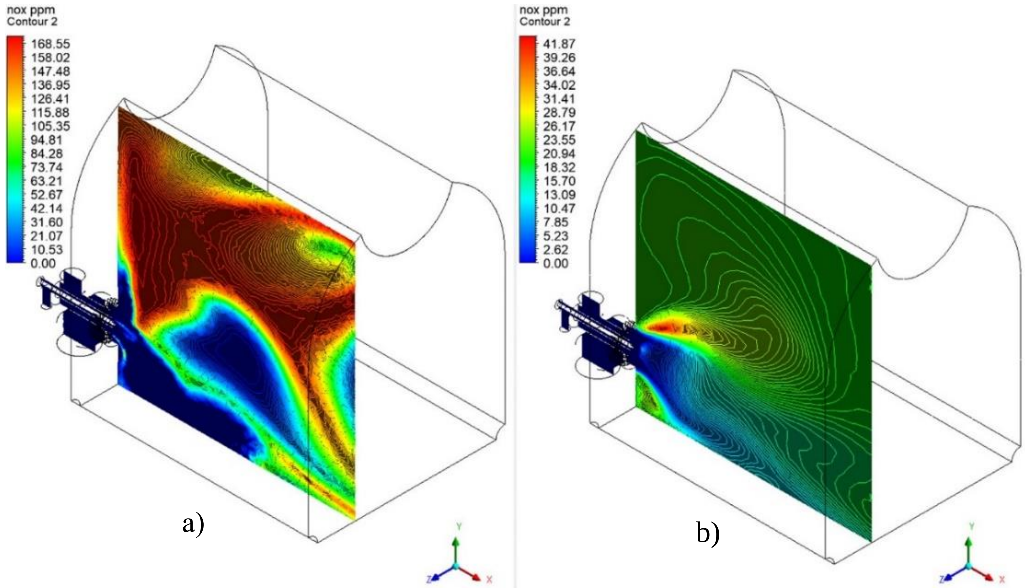


Fig. 4. Distribution of nitrogen oxides in the cross-section of a hot-water boiler furnace during combustion of natural gas (a) and biogas (b).

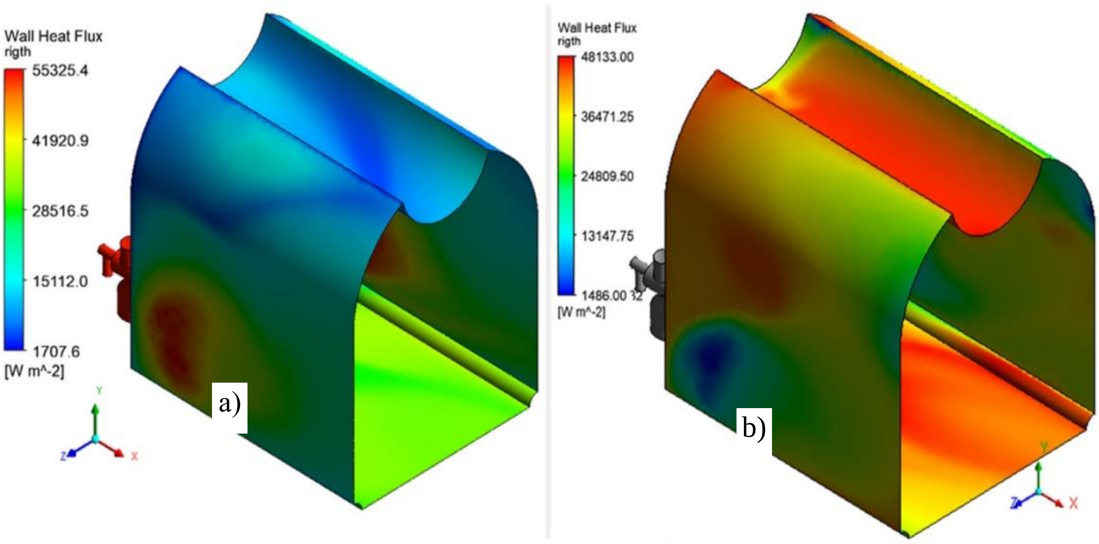


Fig. 5. Distribution of local heat fluxes on the walls of a hot-water boiler furnace during combustion of natural gas (a) and biogas (b).

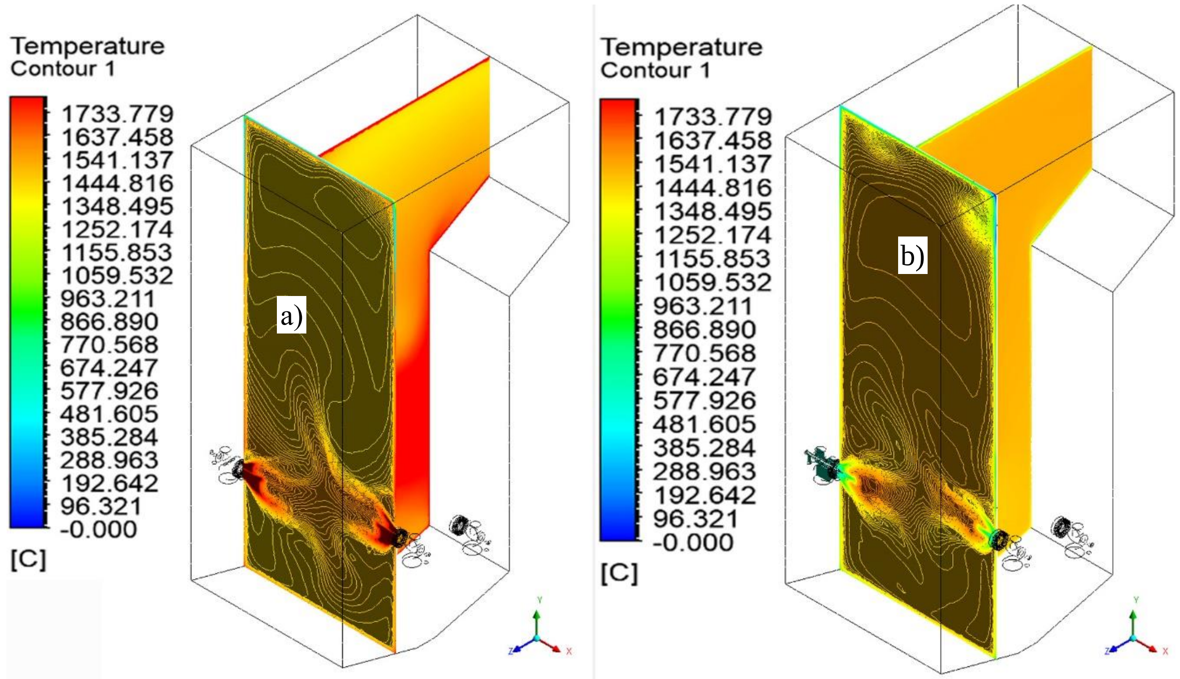


Fig. 6. Temperature field of the fuel in a power boiler during combustion of natural gas (a) and biogas (b)

The environmental aspect (Fig. 7) clearly illustrates the Zeldovich mechanism: the zones of maximum NO_x concentration are localized in regions of highest thermal stress. Natural gas is characterized by a high anthropogenic load due to intensive thermal NO_x formation. At the same time, biogas enables a denitrification regime directly within the combustion process. The reduction in the mass yield of nitrogen oxides is achieved through the combined effect of a lower flame temperature and the presence of inert diluents in the fuel.

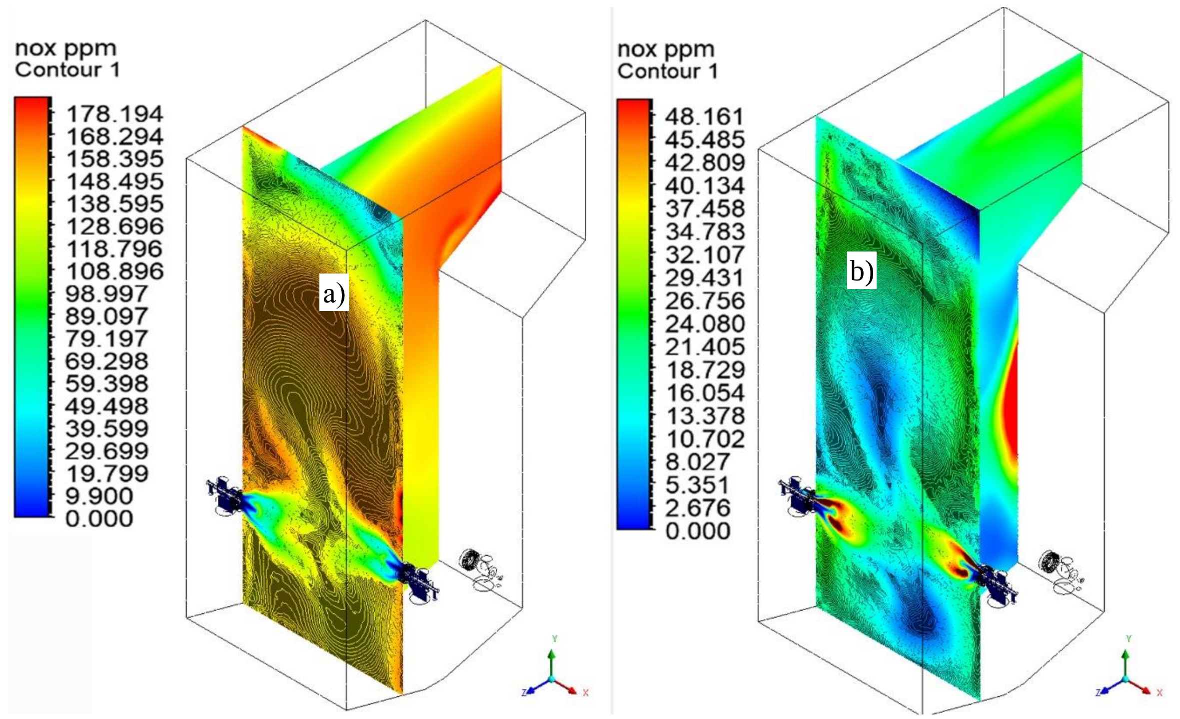


Fig. 7. Distribution of nitrogen oxides (NO_x) inside the furnace of a power boiler during combustion of natural gas (a) and biogas (b).

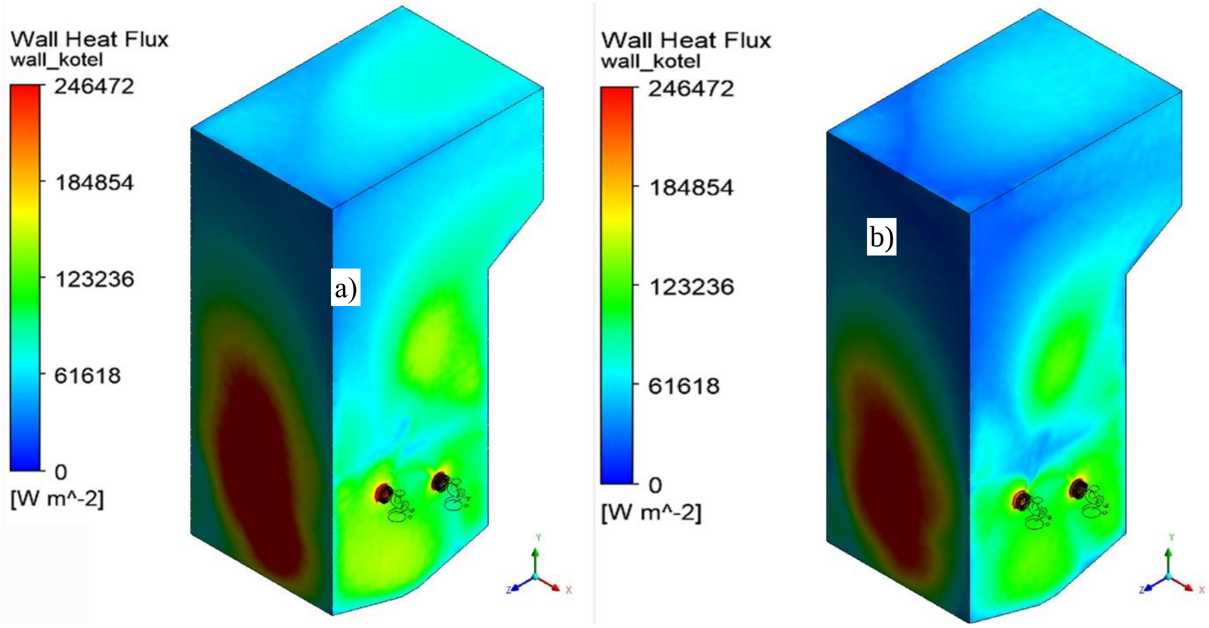
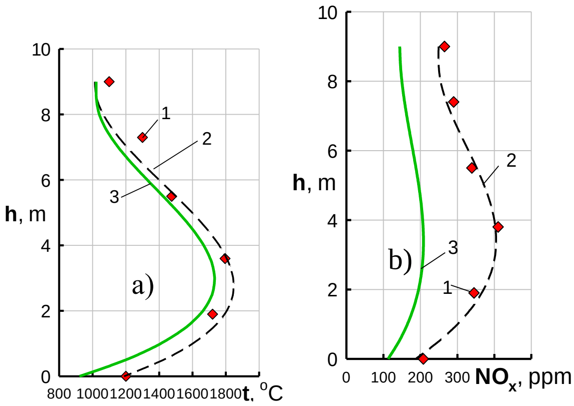


Fig. 8. Distribution of local heat fluxes on the walls of a power boiler furnace during combustion of natural gas (a) and biogas (b).

According to the visualization of temperature fields (Fig. 8), the transition to biogas makes it possible to optimize the thermal state of the heat exchange surfaces of the power boiler. Due to the high emissivity of combustion products containing CO_2, radiative heat transfer becomes more uniform. This helps avoid local tube overheating and significantly reduces the amplitude of thermal stresses. As a result, the risk of low-cycle fatigue in the tube system and drum components is minimized, which directly extends the service life of the equipment. Verification of the furnace temperature field in the CFD model (Fig. 9a) demonstrated excellent agreement (97,5…98,5%) between numerical calculations and experimental measurements [28]. Comparative analysis revealed that replacing natural gas with biogas leads to a reduction in peak temperature in the active zone by 120…140 °C, which substantially decreases thermal NO_x formation. The biogas flame exhibits a gentler temperature gradient, which improves the reliability of waterwall tubes. Despite lower core temperatures, an increase in flue gas temperature at the furnace outlet of 20…25 °C was recorded. This phenomenon, caused by the increased mass flow of combustion products and their high emissivity, allows maintenance of nominal steam parameters while significantly improving the environmental performance of the power unit.

Numerical analysis of emission characteristics of the power boiler (Fig. 10b) confirms the high effectiveness of biogas as a denitrification tool.



1 – experiment [36]; 2 – CFD model of natural gas combustion; 3 – CFD model of biogas combustion

Fig. 9. Comparison of temperature (a) and nitrogen oxide (NO_x) distributions (b) inside a power boiler furnace.

Regardless of the boiler operating regime, a reduction in NO_x concentration within 45–50% compared to conventionб)methane was observed. This is explained by thermal degradation of the flame, which critically affects the rate of nitrogen oxide formation via the Zeldovich mechanism. While natural gas is characterized by a sharp concentration peak at a height of 3.5 m, biogas fuel ensures a more “gentle” distribution of pollutants. Thus, the use of biogas enables the integration of domestic energy facilities into the EU environmental framework, ensuring compliance with emission standards without the use of catalytic neutralization systems.

CONCLUSIONS

Based on the conducted research, which includes numerical CFD modeling of three-dimensional combustion processes and FEA analysis of the thermomechanical state of structural elements, the following scientific and practical results were obtained:

1. A comprehensive mathematical model developed in the ANSYS Fluent environment (incorporating the Species Transport, Realizable $k-\varepsilon$, and Eddy-Dissipation Concept (EDC) models, alongside the Discrete Ordinates (DO) radiation method) has been verified through comparison with experimental data. The discrepancy in temperature fields did not exceed 1,5% to 2,5% (a convergence of 97,5% to 98,5%), which strictly confirms the validity of the adopted assumptions, boundary conditions, and the reliability of the computational algorithm for predicting transient operating regimes.I

2. It was established that the presence of 31% carbon dioxide (CO_2) acting as an inert ballast in the biogas induces thermal degradation of the flame. This manifests as the deconcentration (smearing) of the high-temperature flame core and a reduction in peak local temperatures by 100 to 150 °C compared to mono-component methane fuel.

3. Due to the lower heating value of the biogas mixture (21,5 MJ/Nm^3 versus 35,8 MJ/Nm^3 for natural gas), maintaining the nominal thermal capacity of the boiler requires an intensification of the volumetric fuel flow rate. This causes an increase in the flame reach and shifts the zone of maximum thermal loads toward the rear wall of the furnace chamber.

4. It was shown that despite the reduction in the mass-average temperature within the combustion core, the elevated concentration of triatomic gases (CO_2, H_2O) in the biogas combustion products increases their spectral emissivity (emission coefficient). This factor compensates for the temperature drop, providing an increase in the gas temperature at the furnace outlet by 20 to 25 °C and guaranteeing the stable maintenance of nominal steam parameters.

5. It was proven that the primary mechanism for mitigating the generation of toxic components is the thermal inhibition of nitrogen monoxide formation reactions. The localization of peak NO_x concentration zones correlates strictly with regions of extreme temperatures, confirming the dominance of the thermal mechanism (Zeldovich mechanism) of atmospheric nitrogen fixation.

6. Retrofitting boiler units to biogas fuel provides an integral reduction in nitrogen oxide emissions by 45% to 50% across the entire range of operating loads. This justifies the technological compliance of power plants with stringent EU environmental performance standards solely through operational and regime factors, without requiring capital-intensive secondary catalytic flue gas cleaning systems.

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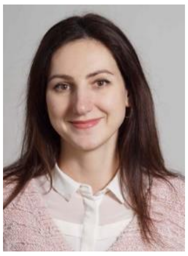

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