Particularities of Thermal Regimes and Emission Characteristics of Hot Water Boilers Operating on Heterogeneous Fuel Pellets

Rachynskyi A.Yu., Chernousenko O.Yu., Baraniuk O.V., Onysko A.I., Tkachenko S.S.

National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Kyiv, Ukraine

Abstract. The aim of this study is to provide a scientific substantiation of the mechanisms of thermochemical conversion of wood pellets and low-grade agrobiomass in the furnace chambers of municipal boilers using multiparameter CFD modeling methods. To achieve this aim, the following tasks were solved: a numerical approach combining the Discrete Phase Method (DPM) and the Laminar Flamelet model was implemented to account for the staged release of volatile matter; the influence of intensive aerodynamic turbulence on particle trajectories was investigated; and the processes of staged air supply were modeled. The scientific novelty of the results lies in establishing the regularities of local reducing zone formation in the flame root during the combustion of high-nitrogen fuels (bottom sludge and poultry manure), for which it was theoretically demonstrated that the vortex effect of turbulence ensures a burnout completeness of the dispersed phase at the level of 98.0–99.2%. The most important results are the proof that staged air supply forms stable reducing zones near the burner, limiting the local NOx concentration to 36 ppm, as well as the mathematical determination of the safe slag-free interval (1000–1150 °C) for the thermal conversion of straw and rapeseed. The practical value of the work consists in the verification of the numerical model based on detailed chemical kinetics approaches, which provides increased accuracy in predicting reducing zones compared with standard Eddy Dissipation models. The significance of the obtained results lies in confirming the possibility of efficient and environmentally safe utilization of low-quality agrobiomass and industrial sludge in serial boiler units. This determines the optimal operating conditions of the equipment and creates a fundamental scientific basis for diversification of the fuel base and extension of the residual service life of thermal power installations under deep load maneuvering.
Keywords: fuel pellets, bioenergy, flame aerodynamics, heat and mass transfer, waste utilization, model verification, environmental safety, surface slagging, energy efficiency.

DOI: https://doi.org/10.52254/1857-0070.2026.3-71.13
UDC: 621.18

Particularitățile regimurilor termice și ale caracteristicilor de emisie ale cazanelor cu apă caldă alimentate cu pelete de combustibil eterogene

Racânskâi A.Iu., Cernousenko O.Iu., Baraniuk O.V., Onâsko A.I., Tkacenko S.S.
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine
Abstract. Scopul acestui studiu este de a fundamenta științific mecanismele de conversie termochimică a peleților din lemn și a agrobiomasei de calitate inferioară în camerele de ardere ale cazanelor municipale, utilizând metode de modelare CFD multiparametrică. Pentru atingerea acestui obiectiv au fost realizate următoarele sarcini: a fost implementată o abordare numerică ce combină Metoda Fazei Discrete (DPM) cu modelul flameletului laminar, pentru a descrie eliberarea etapizată a materiilor volatile; a fost investigată influența turbulenței aerodinamice intense asupra traiectoriilor particulelor; și au fost modelate procesele de alimentare etapizată cu aer. Noutatea științifică a rezultatelor constă în stabilirea mecanismelor de formare a unei zone reducătoare locale în rădăcina flăcării în timpul arderii combustibililor cu conținut ridicat de azot (nămol de fund și gunoi de grajd de pasăre). S-a demonstrat teoretic că efectul de vortex al turbulenței asigură arderea aproape completă a fazei dispersate, atingând un grad de conversie de 98.0–99.2%. Cele mai importante rezultate constau în demonstrarea faptului că alimentarea eșalonată cu aer conduce la formarea unor zone reducătoare stabile în apropierea arzătorului, limitând concentrația locală de NOx la 36 ppm, precum și în determinarea, prin modelare matematică, a intervalului sigur de temperatură fără formarea zgurii (1000–1150 °C) pentru conversia termică a paielor și a rapiței.
Cuvinte-cheie: pelete de combustibil, bioenergie, aerodinamica flăcării, transfer de căldură și masă, utilizarea deșeurilor, verificarea modelului, siguranța mediului, zgurii de suprafață, eficiență energetică.

Особенности тепловых режимов и эмиссионных характеристик водогрейных котлов при работе на разнородных топливных гранулах

Рачинский А.Ю., Черноусенко О.Ю., Баранюк А.Ю., Онисько А.И., Ткаченко С.С.
Национальный технический университет Украины «Киевский политехнический институт им. Игоря Сикорского», Киев. Украина

Abstract. Целью данного исследования является научное обоснование механизмов термохимического превращения древесных пеллет и низкосортной агробиомассы в топочных камерах котлов муниципального назначения методами многопараметрического CFD-моделирования. Для достижения цели решены следующие задачи: реализован численный подход с сочетанием метода дискретной фазы (DPM) и модели Laminar Flamelet для учета стадийности выхода летучих веществ, исследовано влияние интенсивной аэрадинамической турбулизации на траекторию частиц и смоделированы процессы ступенчатого подвода воздуха. Научная новизна результатов заключается в установлении закономерностей формирования локальных восстановительных зон в корне факела при сжигании высокоазотистого топлива (донных илов, птичьего помёта), при которых теоретически доказано, что вихревой эффект турбулизации обеспечивает полноту выгорания дисперсной фазы на уровне 98.0…99.2%. Наиболее важными результатами являются доказательства того, что ступенчатая подача воздуха формирует стабильные восстановительные зоны вблизи горелки с ограничением локальной концентрации NO_x до 36 ppm, а также математическое определение безопасного бесшлакового интервала (1000…1150 °C) для термической конверсии соломы и рапса. Практическая ценность работы заключается в верификации численной модели на базе подходов детальной химической кинетики, обеспечивающей повышенную точность прогнозирования зон восстановления по сравнению со стандартными моделями Eddy Dissipation. Значимость полученных результатов заключается в подтверждении возможности эффективной и экологически безопасной утилизации низкокачественной агробиомассы и промышленных илов в серийных котлоагрегатах. Это определяет оптимальные эксплуатационные режимы оборудования, а также создает фундаментальную научную основу для диверсификации топливной базы и увеличения остаточного ресурса теплоэнергетических установок при глубоком маневрировании нагрузкой.

***Keywords*:** топливные гранулы, биоэнергетика, аэродинамика факела, тепломассообмен, утилизация отходов, верификация модели, экологическая безопасность, шлакование поверхностей, энергоэффективность.

INTRODUCTION

The modern global energy sector is undergoing active transformation driven by the global climate crisis and the need for industrial decarbonization. In this context, renewable energy sources (RES), particularly solid biomass in the form of pellets, are becoming a strategic alternative to fossil fuels. As noted by Etsuko Kinefuchi [1], the pellet industry has successfully positioned itself as a leader in the field of sustainable development, which is confirmed by the experience of the world's largest companies, such as Enviva. The political commitment of the European Union countries, enshrined in the Renewable Energy Directive (RED III), as well as similar measures taken by the South Korean government to increase the share of RES, indicate the irreversible transition to biofuels [2, 3, 4]. In particular, in Poland, the demand for wood pellets is stimulated by air quality improvement programs and subsidies for the replacement of outdated boilers [5].

For an in-depth understanding of the processes occurring in the combustion chamber, it is necessary to consider the combustion of an individual pellet as a multistage process. The studies by Sae Byul Kang [3] and Joon Ahn [6] allow the phases of thermal conversion of wood pellets to be classified into three main regimes:

- Gasification: intensive release of volatile matter at relatively low temperatures.
- Flame combustion: rapid oxidation of combustible gases.
- Char (coke residue) combustion: the final stage of solid carbon oxidation.

Experimental studies have established that the dynamics of changes in fuel mass and volume differ significantly at each stage. In the gasification regime, the mass reduction can reach 37% with an insignificant change in volume (approximately 7%). In contrast, the char combustion stage is accompanied by a sharp decrease in volume (up to 41%) with a smaller change in mass (10%) [1]. It is important to consider that at low ambient temperatures (approximately 500 °C), the gasification stage occupies the largest part of the total conversion time [6]. Ksenia Vershinina [7] also points out the effectiveness of co-combustion of coal sludge with biomass, which improves the ignition characteristics of the mixture.

Studies by Mykola Zhovmir [6] on low-temperature burnout (700 °C) indicate that for short pellets, the process is controlled by an intensive axial diffusion flux, whereas for long pellets, radial burnout is the limiting factor. These data are of practical importance for selecting the optimal pellet geometry in order to minimize mechanical unburned losses [8].

Analysis of the available literature indicates that when using pellets as fuel, the influence of the raw material composition on fuel characteristics should be taken into account. It is known that the expansion of the raw material base through the use of agro-industrial waste is accompanied by changes in the thermophysical and mechanical properties of the fuel:

- Mechanical parameters: Ľubomír Kubik [8] demonstrated that mixtures of wheat and rapeseed straw exhibit higher compressive strength values (up to 7.10 MPa) and modulus of elasticity (14.97 MPa) compared with homogeneous samples.
- Energy density: Pelletization of lignocellulosic biomass (elephant grass, eucalyptus, bagasse) makes it possible to obtain solid biofuel with high energy density, although the high ash content (up to 6.48%) in some types of grasses may deteriorate operational performance [9].
- Inert components: The addition of pine needles to pine shavings or rice straw to wood chips makes it possible to regulate pellet quality in accordance with ISO 17225 standards [10, 11].

Analysis of legume waste (beans) showed that its calorific value (17,1 MJ/kg) is close to that of wood waste, while the emission level during combustion does not exceed permissible limits [12].

A critical aspect of agro-pellet utilization is the specific nature of ash formation. Anna Strandberg [13], using 3D X-ray microtomography, found that poplar fuel forms porous, calcium-rich ash, whereas wheat straw produces a high-density silicate melt. This leads to the formation of bubbles on the char surface, affecting gas transport [13].

Studies by Polish researchers emphasize that the chemical composition of ash is a key indicator for assessing the risks of slagging and fouling of boiler heating surfaces [8].

The efficiency of small-capacity pellet boilers directly depends on the organization of air supply. Đorđe Novčić [14] and Rade Karamarković [15] highlight the importance of staged supply of preheated air for separating gasification and afterburning zones. The implementation of refractory inserts and innovative burners (top-fed or moving grate burners) makes it possible to stabilize the flame and increase efficiency. Grzegorz Pelka [16] found that the average CO and NO_x values are similar for different types of burners when operating at full load. Luigi Francesco Polonini [8] demonstrated that increasing the depth of the burning pot makes it possible to reduce particulate matter (PM) emissions to 6…16 mg/Nm^3.

To stabilize boiler operation under varying pellet quality, Sae Byul Kang [3] proposed an air–fuel mixture control system based on oxygen sensors and a PID controller. Such a system maintains the O_2 concentration in flue gases at a level of 8,5% ± 1% [3, 17].

Pellet boilers are a significantly cleaner alternative to wood-burning stoves. The studies by Michael Priestley [18] indicate that pellet particulate emissions consist of 90% substituted monoaromatic compounds, whereas wood combustion produces 3…55 times more polycyclic aromatic hydrocarbons (PAHs).

A study of co-combustion of wood pellets with wheat seeds [19] revealed that an increase in the wheat fraction leads to higher CO and NO_x emissions due to the higher nitrogen content in agricultural raw materials and suboptimal combustion chamber aeration. Similar results were obtained by O.A. Siryi [5] for rapeseed pellets, where the necessity of precise adjustment of the feeding system depending on the release of volatile fuel components was established. Even at low temperatures (800…1200 °C), the combustion of individual large pellets demonstrates complex NO and SO_2 release dynamics dependent on the air flow rate [20].

The application of computational fluid dynamics (CFD) methods is an integral tool in design processes. Modeling makes it possible to optimize air distribution, as well as the number and arrangement of openings in gasification chambers [14, 21]. Numerical methods are also used to analyze the influence of conical turbulators on heat transfer intensification [22] and to predict the thermodynamic efficiency of agro-pellet utilization systems [23].

The use of pellet boilers in Ukraine today is not merely relevant but represents a strategically important direction. Considering the state of the Integrated Power System (IPS) and the constant risks to the gas transmission network, pellets have become one of the most reliable means of decentralizing heat supply.

Why is this relevant today?

The first answer to this question is Ukraine’s aspiration for energy independence, since pellets are produced from domestic raw materials (wood-processing waste, straw, sunflower husks), which makes consumers independent of imported gas. At the same time, unlike conventional wood-fired boilers, pellet units operate automatically (fuel feeding, ignition, and temperature maintenance), bringing their comfort level closer to that of gas-fired systems.

Furthermore, pellets are a «carbon-neutral» fuel, which corresponds to the European course toward decarbonization and Ukraine's recovery programs.

For businesses and public institutions, pellet heating is often less expensive than gas, especially during periods of peak natural gas prices.

Based on the analysis of the available literature sources, the authors formulated the objective of the study:

Scientific and methodological substantiation and numerical modeling of three-dimensional heat and mass transfer processes, aerodynamics, and the kinetics of harmful emission formation in the furnace chambers of low-capacity boilers during their conversion from conventional wood to alternative types of low-grade biofuel (agro-pellets and bottom sludge).

To achieve the stated objective, the following scientific and practical tasks were addressed in the study:

- Establishment of general regularities in the formation of spatial temperature fields and thermodynamic stability of the flame core during the combustion of fuel pellets with different physicochemical and raw material compositions.
- Mathematical modeling and quantification of the completeness of thermochemical conversion of the dispersed phase (Particle Burnout parameter) depending on the structure and intensity of swirl generation in the near-wall vortex flow within the burner device.
- Identification of cause-and-effect relationships between local aerodynamic characteristics of the furnace environment and the kinetics of nitrogen oxide (NO_x) formation in order to minimize anthropogenic impact during the thermal conversion of high-nitrogen agrobiomass.

METHODS

To accomplish the stated objectives, a mesh-volume model was developed based on the geometry of the prototype boiler and a system of boundary conditions implemented in the ANSYS Fluent software package [24]. The automated boiler Kotlant KGP 25 was selected as the basic research object. Its design is characterized by the presence of double steel walls (6 mm thickness), forming a water jacket for the circulation of the heat-transfer medium. The outer part of the casing is equipped with an insulation layer and a decorative cover. The general design of the boiler is illustrated in Fig. 1. The unit is equipped with an automatic fuel supply system (pellets, coal, sawdust), but can also operate in manual mode when a grate is installed.

This boiler operates based on the principle of automatic fuel supply (pellets or coal) from the hopper to the burner device using a screw mechanism. The electronic controller regulates the feed rate and fan operation, allowing the boiler to maintain the set temperature and operate autonomously for 3 to 7 days on a single fuel load.

Pellet consumption depends on the heat losses of the building and fuel quality. When operating at nominal capacity, it is approximately 5,9 kg/h.

Approximate consumption indicators:

- Maximum consumption: up to 140 kg per day (during continuous operation at full capacity under peak negative temperature conditions).
- Average consumption: for an area of 250 m^2, it is typically 48…96 kg per day, depending on the outdoor air temperature and the level of building insulation.
- Autonomy: due to the 250 dm^3 hopper capacity, a single full pellet load can provide autonomous operation for a period of 3 to 7 days.

The model is also universal: provided that a grate is installed, the boiler can be converted to manual mode for combustion of wood logs or large-piece coal.

In the presented work, computational fluid dynamics (CFD) methods were used to investigate heat transfer and hydrodynamic processes during the combustion of biofuel pellets in furnace devices. The numerical solution of the system of mass, momentum, and energy conservation equations was performed using the ANSYS Fluent software package. The modeling is based on the system of steady-state Reynolds-averaged Navier-Stokes (RANS) equations [24]:

Continuity equation:

$$\frac{\partial \rho}{\partial \tau} + \nabla\left(\rho v\right) = S_m , \qquad (1)$$

where S_m is the source term accounting for the mass added to the gas phase from the pellets. The use of the source term S_m is necessary to account for intensive interphase mass transfer interactions, since a significant amount of moisture and volatile matter is released into the gas medium during the thermal decomposition of pellets.

Momentum conservation equation:

$$\frac{\partial}{\partial \tau}(\rho v)+\nabla(\rho v u)=-\nabla p+\nabla \bar{\tau}+\rho g+F, \qquad (2)$$

where $\bar{\tau}$ is the stress tensor, F is the interaction force with the discrete phase.

This form of the equation was selected to account for the force F (interaction with the discrete phase), which makes it possible to correctly model the influence of fuel particles on the flow aerodynamics inside the furnace.

A semi-empirical Realizable k–ε model with wall functions was used to simulate turbulence, ensuring stable convergence for internal flows in combustion chambers. The Realizable k–ε model was selected because of its ability to provide a more accurate calculation of the dissipation rate and improved modeling of flow separation and vortical structures characteristic of modern pellet burners with tangential air supply:

$$\frac{\partial \rho k}{\partial \tau}+\frac{\partial}{\partial x_j}\left(\rho k x_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\rho\frac{\partial \rho k}{\partial x_j}\right]+, \\ +G_k+G_b-\rho\varepsilon \qquad (3)$$

Heat transfer was accounted for through convection, conduction, and radiative heat exchange. Since the combustion products contain triatomic gases and solid particles, the Discrete Ordinates (DO) radiation model was employed to simulate radiative heat transfer, enabling accurate calculation of local heat fluxes to the furnace walls. The motion and thermochemical conversion of fuel pellets were modeled using the Lagrangian approach (Discrete Phase Model, DPM) [24, 25].

Force balance equation for a particle:

$$\frac{\partial v_p}{\partial \tau}=F_D\left(v-v_p\right)+\frac{g\left(\rho_p-\rho\right)}{\rho_p}, \qquad (4)$$

where $F_D(v - v_p)$ – is the drag force.

The Lagrangian approach was selected because it makes it possible to track the trajectory of each individual pellet, which is essential for analyzing the residence time of agro-pellet particles in the combustion zone to ensure their complete burnout.

The particle trajectories were calculated by integrating the force balance acting on each pellet in the gas flow. The DPM model included the following sequential submodels:

- Heating and moisture evaporation:

$$\frac{\partial T_p}{\partial \tau}=\frac{f_h \pi d_p^2\left(T_\infty-T_p\right)}{m_p C_p}, \qquad (5)$$

- Devolatilization (volatile matter release): the Single Rate or Constant Rate model was used to describe the thermal decomposition of biomass. The Single Rate model was selected as an optimal compromise between computational cost and accuracy for woody biomass, since its kinetic parameters (activation energy E and pre-exponential factor A) have been well studied and validated for rapid pyrolysis processes. The volatile matter release rate was determined according to the Arrhenius law:

$$\frac{\partial m_p}{\partial \tau}=-k\left[m_p-\left(1-f_{v,0}\right)m_{p,0}\right], \qquad (6)$$

where $f_{v,0}$ is the initial volatile matter fraction in the pellet.

$$k=A\exp\left(-E/RT_p\right), \qquad (7)$$

- Char combustion: a Diffusion-Limited Surface Reaction model was employed, accounting for both the oxygen transport rate to the particle surface and the chemical reaction rate. This model was selected because, at the high temperatures prevailing in the boiler furnace, the burnout rate of pellet carbon is limited primarily by the oxygen diffusion rate to the pellet surface rather than by the chemical reaction kinetics.

Reaction rate at the particle surface:

$$\frac{\partial m_p}{\partial \tau}=-4\pi d_p D_{ox}\frac{C_{ox}T_\infty}{T_p+T_\infty}, \qquad (8)$$

where D_{ox} is the oxidizer diffusion coefficient.

To model chemical reactions and volatile matter combustion, the Eddy-Dissipation Model (EDM) was employed, in which the reaction rate is limited by the intensity of fuel–oxidizer mixing. The Eddy-Dissipation Model (EDM) was selected because of the high intensity of biomass volatile combustion reactions, where the process rate is governed by the rate of turbulent mixing between the fuel and air rather than by microscopic chemical kinetics. The oxidation reaction rate, $R_{i,r}$, is limited by the intensity of turbulent mixing («the fuel meets the oxidizer»):

$$R_{i,r} = \min\left[\begin{array}{l} v'_{i,r} M_{\omega,i} A\rho \dfrac{\varepsilon}{k} \dfrac{Y_R}{v'_{i,R} M_{\omega,R}}, \\ v'_{i,r} M_{\omega,i} AB\rho \dfrac{\varepsilon}{k} \dfrac{\sum_p Y_R}{\sum_j v''_{i,j} M_{\omega,j}} \end{array}\right], \quad (9)$$

where Y_R is the mass fraction of the reactant, and Y_P is the mass fraction of the combustion products.

Radiative heat transfer (DO Model). The Discrete Ordinates (DO) model is the most versatile because it allows radiation scattering by solid fuel and ash particles to be taken into account, which is essential for accurately calculating heat fluxes to the walls of pellet-fired boilers. The Radiative Transfer Equation (RTE) for the radiation intensity I in the direction s is given by:

$$\nabla(I(r,s)s) + (a+\sigma_s)I(r,s) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(r,s')\Phi(s\cdot s')d\Omega', \quad (10)$$

This model makes it possible to account for flame shielding and heat fluxes to the furnace walls.

The NO_x concentration was calculated by means of post-processing, taking into account both the thermal NOx (Thermal NO_x) and fuel NO_x (Fuel NO_x) formation mechanisms, which is essential for evaluating the environmental performance of the transition to agro-pellets. NO_x modeling was performed to assess the environmental effect of using agro-pellets (e.g., those produced from sunflower husks or sludge), which have a higher nitrogen content than natural gas and therefore require prediction of fuel NO_x concentrations.

For agro-pellets (with a high nitrogen content), the fuel NO_x (Fuel NO_x) mechanism is dominant. The formation rate is described by the transport equation for the NO concentration [26]:

$$\frac{\partial(\rho Y_{NO})}{\partial\tau} + \nabla(\rho v Y_{NO}) = \nabla(\rho D_{eff}\nabla Y_{NO}) + S_{NO}, \quad (11)$$

The source term SNO accounts for the reactions converting nitrogen-containing volatile species (HCN, NH_3) into NO. The geometric model was developed in the ANSYS Design Modeler environment in accordance with the drawings of the experimental facility (e.g., a low-capacity boiler). A hybrid computational mesh (Hexa/Tetra) with local refinement in the active combustion zones and near the air supply nozzles was generated to discretize the computational domain. As part of the validation procedure, a mesh independence study was performed by comparing the results obtained using meshes with different numbers of elements. In addition, the hydrodynamic parameters of the flue gases at the boiler outlet predicted by the CFD simulations were compared with the corresponding values specified in the boiler technical documentation.

Figure 1 shows the unstructured hybrid mesh consisting predominantly of tetrahedral elements. A significant mesh refinement can be observed in the burner region (shown at an enlarged scale and enclosed by a red frame in the lower fragment). This is essential for accurately modeling the active combustion zone, where intensive chemical reactions occur and high temperature gradients are present.

The uniformity of the elements in the convective section (upper passages) ensures stable calculation of flue gas flow without excessive computational error. The model includes the internal furnace volume and a multi-pass convective flue gas passage. The segmented configuration of the gas passages in the upper section is intended to increase the residence time of the gases within the boiler and to intensify heat transfer to the water jacket, reflecting the actual design of the industrial prototype.

Boundary conditions:

- *Inlet*: the air flow rates (Primary Air/Secondary Air) and fuel temperature were specified. In Fig. 1, these are indicated by red vectors. Since the boiler was equipped with a standard retort-type pellet burner, the boundary conditions at this location included the primary and secondary air supply parameters, as well as the initialization of the fuel discrete phase (DPM). The vectors indicate the flow direction, representing the aerodynamics of the forced-air supply.
- *Outlet*: a Pressure Outlet boundary condition was specified. According to the boiler specifications, the pressure at the chimney outlet should correspond to a draft of 25 Pa, which was prescribed in the numerical model. In Fig. 1, the

outlet nozzle (Pressure Outlet) is indicated by blue vectors in the upper section. This boundary represents the exit through which the combustion products leave the boiler after passing through all stages of heat transfer.

- *Walls*: a fixed wall temperature was specified to model the cooled furnace walls.

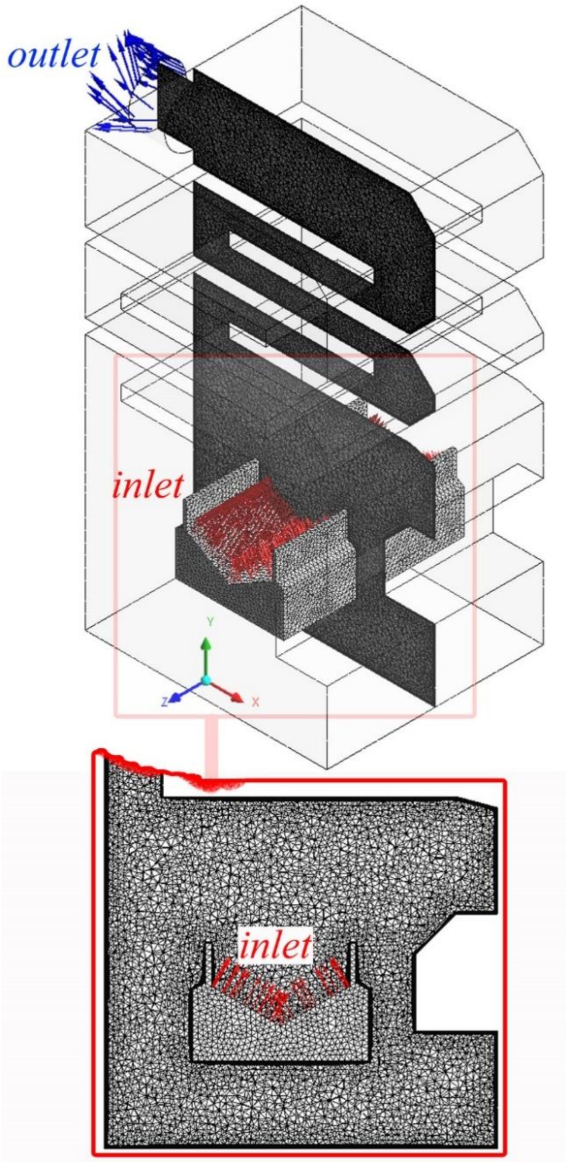

Fig. 1. Image of the boiler computational mesh.

The next stage after determining the gas-dynamic parameters was the configuration of the diffusion-type combustion model (non-premixed combustion).

The basis of this approach is the generation of a preprocessor file in the form of PDF tables (Probability Density Function), which serve as a database for ANSYS Fluent. These tables contain calculated relationships between the local fuel mixture fraction, chemical species concentrations, and temperature parameters.

To ensure high reliability of the results during the combustion of heterogeneous biomass, the chemical characteristics of the fuel were specified based on elemental analysis both for the as-received state and recalculated on a dry ash-free basis (Table 1).

The calculation of the PDF tables was based on the principles of chemical equilibrium (Equilibrium Chemistry). This approach, unlike the simplified Eddy-Dissipation Model, makes it possible to account for dissociation processes and the formation of intermediate radicals, thereby providing a more physically accurate flame temperature profile. Particular attention was paid to the accuracy of environmental impact prediction.

To detail the mechanisms of nitrogen oxide formation, the Laminar Flamelet concept was applied. This made it possible to integrate the effects of aerodynamic flame stretching into the model and account for nonequilibrium phenomena, in particular sub-equilibrium temperature effects and super-equilibrium radical concentrations, which is critically important for the accurate assessment of NO_x emissions when using agro-pellets.

RESULTS AND DISCUSSION

The object of numerical modeling was a solid-fuel hot-water boiler. Structurally, this unit implements the principle of shaft-type fuel combustion with a lower combustion surface and a vertical convective section.

The organization of the process within a confined lower layer of the fuel bed makes it possible to stabilize the thermal potential of the flame and ensure efficient primary and secondary air supply, which reduces heat losses due to chemical incomplete combustion (q_3) as well as emissions of nitrogen and carbon oxides during the combustion of renewable biomass fuels (wood, pellets, briquettes).

The results of modeling the temperature regime in the longitudinal and transverse sections of the boiler furnace are presented below.

During the combustion of hardwood pellets (Fig. 2), the zone of maximum temperatures (red core) is located somewhat farther from the fuel bed compared with softwood pellets. This is explained by the higher thermal inertia of hardwood: the particle requires more time for heating and the onset of intensive gasification. The flame core remains stable, with temperatures in the range of 1100–1250 °C. This ensures reliable burnout of heavy carbon chains characteristic of hardwood.

Table 1.

Fuel characteristics on an as-received basis [29]

Parametr	Hardwood pellets	Mixed-species wood pellets	Softwood pellets	Rapeseed pellets	Poultry manure and straw pellets	Bottom sludge pellets
C^p	41,568	43,21	46,44	31,56	34,700	30,32
H^p	5,196	5,183	5,85	4,46	4,071	4,06
O^p	38,970	39,45	41,59	38,68	25,232	19,85
N^p	0,061	0,044	0,076	0,622	3,653	2,782
S^p	0,026	0,009	0,057	0,064	0,592	0,694
W^p	9,00	0,80	0,40	5,40	13,50	21,80
A^p	5,18	10,6	5,2	14,9	7,6	4,4
V^{daf},%	70,0	75,8	79,2	62,5	63,6	59,5
LHV_{ar}, *MJ/kg*	14,97	15,67	17,234	10,94	12,93	11,82

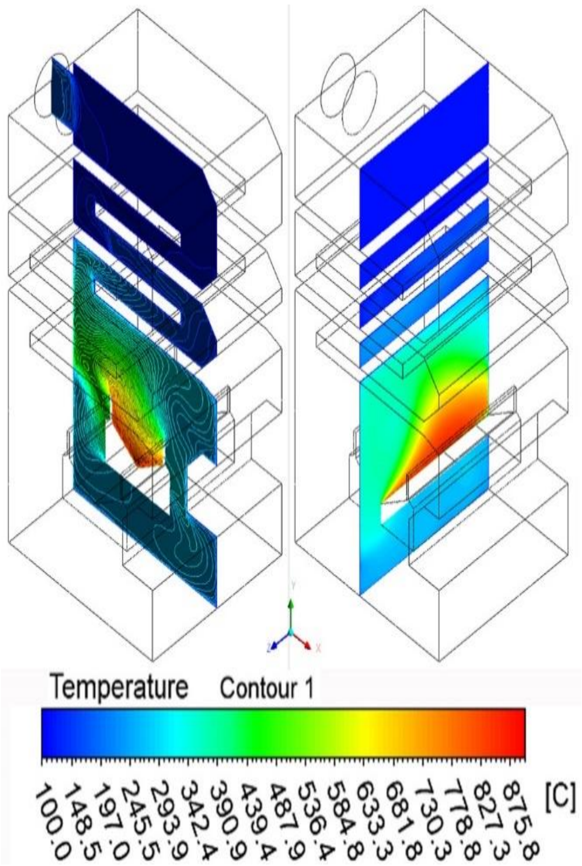

Fig. 2. Temperature field in the longitudinal and transverse sections of the boiler combustion chamber during the combustion of hardwood pellets.

During the combustion of mixed wood of different species (Fig. 3a), the central red zone corresponds to temperatures of 1100…1250 °C.

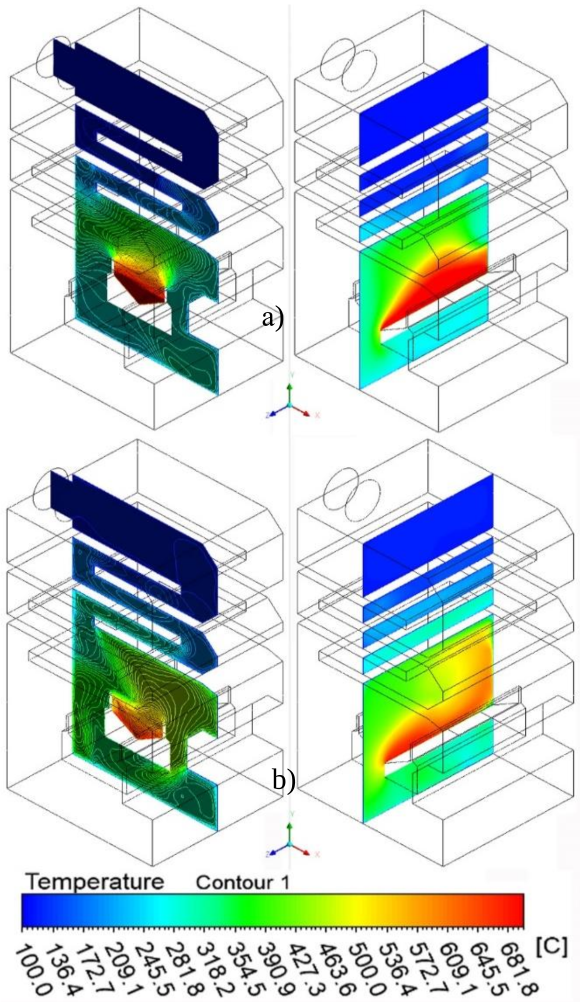

Fig. 3. Temperature field in the longitudinal and transverse sections of the boiler furnace during the combustion of poultry manure and straw pellets (a) and bottom sludge pellets (b).

This represents a «healthy» combustion regime: the temperature is sufficient for complete decomposition of tars and heavy hydrocarbons characteristic of hardwood species, while remaining below the threshold of intensive thermal nitrogen oxide formation. Flame stability: despite the heterogeneity of the fuel (mixed wood), the flame maintains a stable geometric shape. This indicates effective aerodynamic preparation of the fuel–air mixture in the burner unit.During the combustion of softwood pellets, the active combustion zone begins almost immediately at the burner outlet. This is characteristic of softwood species due to their ability to undergo rapid gasification. The flame core is characterized by a high temperature potential (1150…1300 °C), indicating intensive combustion of resinous compounds. The flame appears to be the most homogeneous compared with other fuel types (sludge or agro-pellets), indicating high process stability.

Rapeseed pellets have a high calorific value. The high concentration of heat release indicates rapid oxidation of volatile matter. The flame core is stabilized within the range of 1050…1200 °C. This is critically important because rapeseed ash begins to melt at relatively low temperatures. The model demonstrates that the boiler control system maintains the temperature below the threshold of intensive slagging while preserving a high reaction rate.

During the combustion of pellets made from poultry manure and straw, the straw component in the pellet ensures rapid release of volatile matter, which is observed as an intensive flame initiation (Fig. 3a).

This contributes to stable ignition of the mixture. The maximum temperatures are concentrated in the central part of the flame. For the mixture containing poultry manure, it is critically important that the model predicts temperatures within the range of 1000…1100 °C. This is a «safe window» that allows complete combustion of organic matter while preventing extensive softening of poultry manure ash, which has a low deformation temperature.

During the combustion of bottom sludge pellets (Fig. 3b), the active combustion zone is slightly shifted or has a smaller area compared with wood pellets.

This is associated with the ballast effect of mineral substances contained in the sludge, which absorb part of the heat for their own heating. The core temperature is maintained within the range of 1050…1150 °C, representing a compromise: it is sufficient for burnout, but remains below the melting temperature of the specific sludge ash, thus preventing vitrification.

To determine the completeness of the thermochemical conversion of fuel pellets, which reflects the fraction of combustible mass transferred into the gas phase as a result of devolatilization and char residue oxidation, the CFD modeling results are also presented in the form of the distribution of the «Particle Burnout Degree» parameter (Figs. 5–7).

The use of this parameter within the framework of CFD modeling makes it possible to quantitatively assess the level of mechanical incomplete combustion and the overall energy efficiency of the boiler, as well as to clearly localize the zones of reaction completion within the furnace space for different types of biomass. The analysis of particle burnout fields confirms that the selected aerodynamic flow structure provides sufficient residence time of the fuel in the high-temperature zone, allowing a burnout degree of 98…99% to be achieved and minimizing the emission of harmful CO and soot pollutants.

During the combustion of hardwood pellets, the model (Fig. 4) records strong flow swirling. In solid-fuel boilers of this type, this is critically important: the vortex keeps heavy oak or beech particles within the high-temperature zone for a longer period, allowing them to be completely oxidized before entering the convective section. Hardwood species have a dense char structure, which burns out more slowly, as demonstrated in Fig. 5. The particle burnout degree for hardwood pellets in the model reaches 98.5–99%. It can be seen that by the time the particles exit the furnace, the fuel concentration gradient has almost completely disappeared (transition to the blue color).

Since mixed wood contains components with different volatile matter release rates, the burnout zone (Fig. 6a) appears more extended compared with pure softwood species. The model demonstrates very high efficiency – at the furnace outlet, fuel particles have almost completely transitioned into the gaseous phase (the blue region at the end of the flame).

For mixed wood, this parameter in solid-fuel boilers reaches 98,5…99,2%, which minimizes mechanical incomplete combustion.

During the combustion of softwood pellets, the ash melting temperature of softwood is typically high (above 1200 °C), while the ash content is low (up to 0,5…0,7%); the model shows no signs of «heavy» particles falling out of the flow. This minimizes the load on the grate cleaning system.

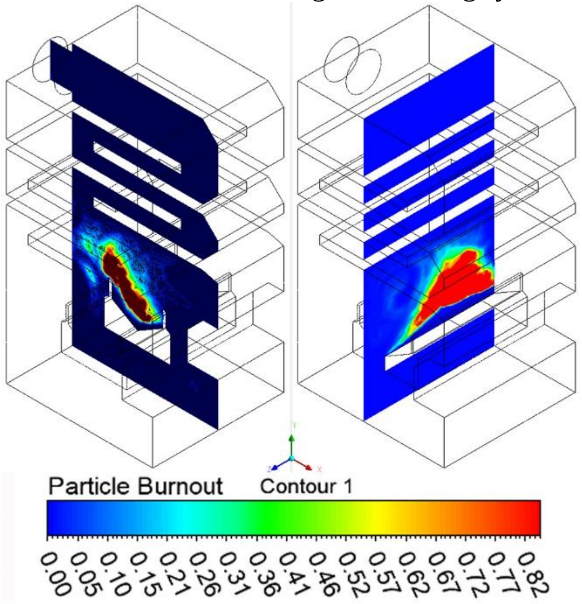

Fig. 4. Particle burnout degree in the longitudinal and transverse sections of the boiler furnace during the combustion of hardwood pellets

The absence of blue trails of unburned material (soot) in the convective zone confirms that, during softwood combustion, the boiler operates in the most environmentally friendly mode with minimal CO emissions.

During the combustion of rapeseed pellets, the presence of oil-containing components may lead to the formation of sticky deposits in the case of incomplete combustion, which indirectly indicates efficient burner operation. The intense flow displaces combustion products away from the nozzle. The burnout gradient in the figure demonstrates that the fraction of unburned carbon is minimal at the burner outlet. The blue zones at the end of the chamber confirm the efficiency of the final oxidation stage – the burnout degree of rapeseed particles reaches 97…98%.

During the combustion of poultry manure and straw pellets (Fig. 5a), the particle burnout degree (represented by the gradient distribution) shows that by the end of the combustion chamber, the majority of the fuel has transitioned to the complete oxidation phase.

Since manure burns more slowly than straw, the swirling nature of the flow (visualized through particle trajectories) forces the heavier manure particles to circulate within the hot zone for a longer period. The model shows that fine ash (which is abundant in agro-pellets) is uniformly transported into the convective section. The boiler design directs the flows in such a way that aggressive straw ash (rich in chlorides) does not accumulate near the walls, minimizing the risk of high-temperature corrosion.

Unlike wood, where burnout occurs almost instantaneously within the flame, the combustion of bottom sludge pellets is characterized by a more «extended» zone of the highest concentration of solid particles (Fig. 5b). This indicates that bottom sludge contains a higher proportion of char residue, which requires more time for complete oxidation.

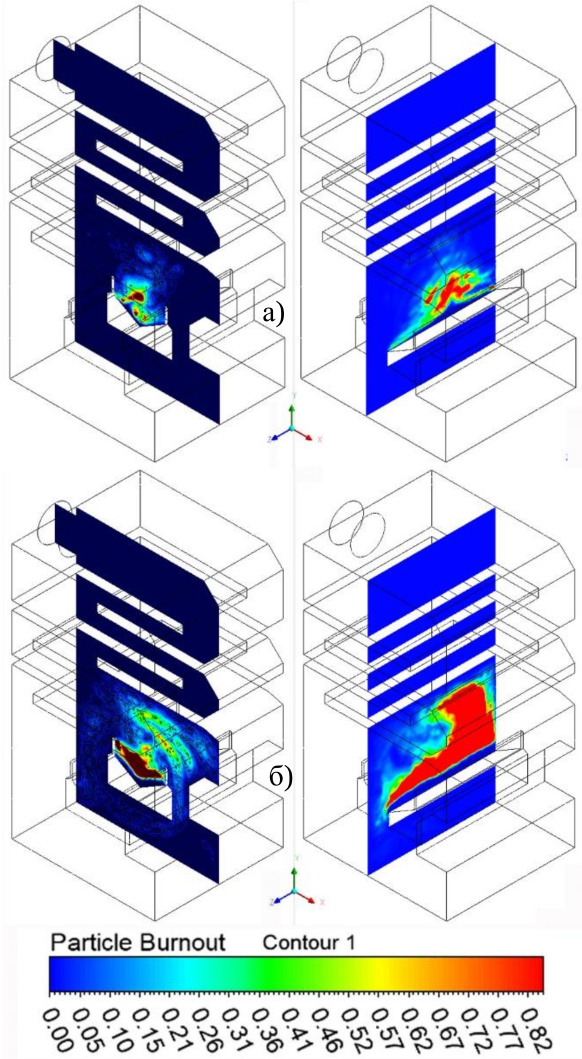

Fig. 5. Particle burnout degree in the longitudinal and transverse sections of the boiler furnace during the combustion of poultry manure and straw pellets (a) and bottom sludge pellets (b).

In the lower part of the model (Fig. 5a), the velocity distribution promoting the removal of the fine ash fraction can be observed. Since sludge contains a significant amount of inorganic matter, the boiler design demonstrated by the model shows how air flows «wash» around the grate section, preventing local overheating and the adhesion of sludge deposits to the metal surfaces. For this type of fuel, a burnout degree of 94…96% is considered an excellent result. The blue color at the combustion chamber outlet confirms that the majority of the organic matter in the sludge has been converted into thermal energy.

Thus, the analysis of the Particle Burnout parameter distribution is fundamental for confirming that the selected air supply strategy ensures the maximum possible energy release per unit mass of fuel.

The implementation of strategies aimed at reducing anthropogenic environmental impact requires preliminary monitoring of NO_x generation during the thermal conversion of pellets. Based on the developed boiler model, maps of nitrogen oxide distribution in different planes were constructed (Figs. 6–7), confirming the complex spatial nature of their formation. The obtained pollutant concentration data are presented in parts per million (NO_x [ppm]), ensuring a correct comparison of the results with regulatory indicators.

The analysis of Fig. 6 shows that a dark blue zone (0…36 ppm) corresponding to the minimum NO_x concentration is observed in the lower part of both sections. This confirms the staged nature of combustion: pyrolysis and reduction processes occur in the initial zone, which suppresses intensive nitrogen oxide formation. Comparison of the two sectional planes confirms the three-dimensional nature of nitrogen oxide generation. The left fragment (longitudinal section) shows a complex isoline structure reflecting the influence of aerodynamic flows on the local particle concentration, whereas the right fragment (cross-section) demonstrates a more symmetrical expansion of the flame.

As also shown in Fig. 6, as the flue gases move toward the upper part of the combustion chamber, the NO_x concentration increases. This is caused by the completion of oxidation reactions of nitrogen-containing fuel components and by the thermal mechanism of NO_x formation in high-temperature zones. At the furnace outlet and in the horizontal gas passages, the distribution becomes more homogeneous (uniform). The concentration values stabilize within the range of 145…182 ppm, which corresponds to environmental standards for modern pellet-fired installations of this capacity. According to the color scale, peak concentrations (above 250 ppm) are localized only in individual zones and do not have a dominant influence on the overall emission profile.

During the combustion of mixed wood of different species, a zone with minimum NO_x values (blue color, 0…36 ppm) is observed in the lower part of the furnace and directly near the burner. This is explained by the physics of staged combustion: in this region, endothermic pyrolysis processes and volatile matter release predominate, accompanied by the formation of a reducing environment that suppresses nitrogen oxidation. With increasing distance from the burner, a gradual increase in nitrogen oxide concentration is observed (transition to yellow-green shades). This indicates intensive burnout of fuel-bound nitrogen and the formation of thermal NO_x in zones of active heat release. In the convective passages at the furnace outlet, the NO_x concentration stabilizes within the range of 145…182 ppm. For mixed wood, this value is considered optimal, as it remains below the threshold of intensive harmful emission formation, confirming the environmental feasibility of using this type of fuel. The analysis of the data presented in Fig.10a also indicates the absence of extensive zones with concentrations exceeding 250 ppm. This demonstrates the effective organization of air supply, ensuring a homogeneous temperature field and preventing local overheating.

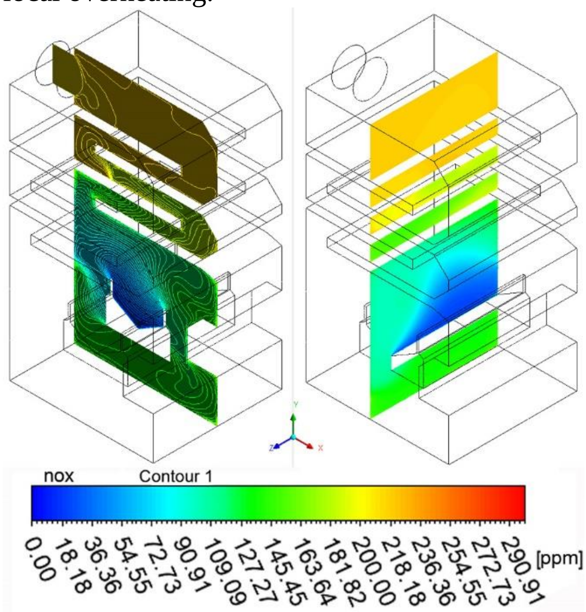

Fig. 6. Distribution of nitrogen oxides in the longitudinal and transverse sections of the boiler furnace during the combustion of hardwood pellets.

During the combustion of softwood pellets, the concentration field becomes homogeneous in the upper part of the furnace and in the convective gas passages, stabilizing within the range of 145…182 ppm.

For softwood species characterized by specific contents of resinous compounds and nitrogen, such values indicate the stability of the thermal regime and the absence of significant emission fluctuations.

Individual zones with concentrations exceeding 230 ppm are practically absent in the cross-sections, indicating effective flame cooling and prevention of significant formation of «thermal» NO_x.

Compared with mixed wood, softwood pellets demonstrate a more uniform distribution of nitrogen oxides throughout the furnace volume in the cross-section, which is associated with the specific kinetics of volatile component burnout.

The calculations also indicate that the boiler aerodynamics ensures environmentally safe combustion of softwood pellets with a low NO_x formation level due to the organized staged air supply.

Rapeseed pellets are typically characterized by a higher nitrogen content compared with wood. The active NO_x formation zone begins at a higher position than for wood pellets, which is associated with the intensive release of volatile matter characteristic of rapeseed.

In the upper part of the furnace and in the convective bundle, the NO_x concentration stabilizes within the range of 163…200 ppm.

This value is slightly higher than that for woody biomass; however, it remains within the acceptable environmental limits for equipment of this capacity.

The modeling results presented in Fig. 10 confirm the possibility of environmentally safe combustion of rapeseed pellets in this boiler.

Pellets made from poultry manure and straw (Fig. 7) are characterized by a specific chemical composition with a high content of fuel-bound nitrogen.

Compared with woody biomass, zones with moderate NO_x concentrations (109…145 ppm) occupy a larger volume of the furnace already during the initial stages of flame development. In the convective channels, the concentration stabilizes within the range of 182–218 ppm.

This value is higher than for wood-based fuels but is an expected result for straw and manure; nevertheless, the obtained indicators remain within controllable limits.

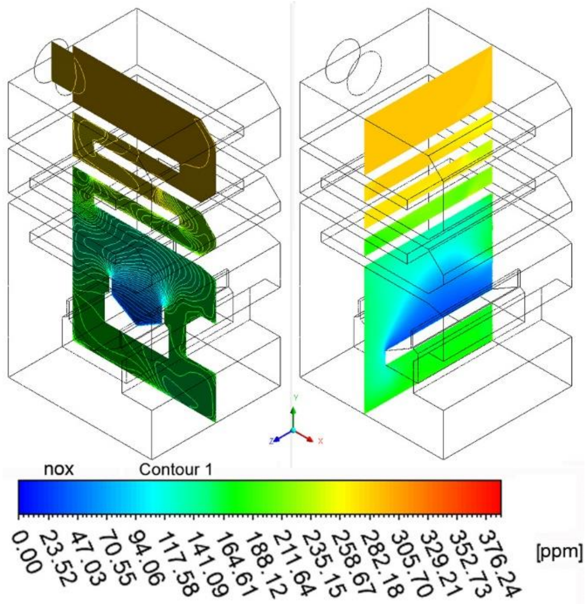

Fig. 7. Distribution of nitrogen oxides in the longitudinal and transverse sections of the boiler furnace during the combustion of poultry manure and straw pellets.

The combustion of bottom sludge (Fig. 8) has a unique thermophysical nature due to its high ash content and the specific characteristics of volatile matter release. Due to the ballast effect of the mineral fraction of the fuel, Fig. 12 shows the most uniform NO_x distribution field in the cross-section. The maximum concentration values are shifted upward in the combustion chamber, indicating a more extended oxidation process of nitrogen-containing compounds over time.

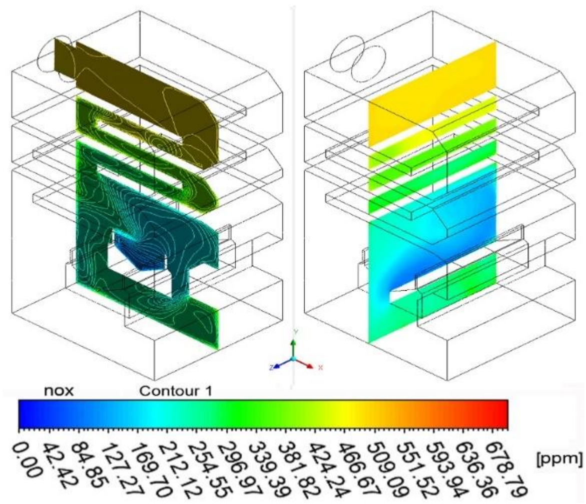

Fig. 8. Distribution of nitrogen oxides in the longitudinal and transverse sections of the boiler furnace during the combustion of bottom sludge pellets.

The NO_x concentration at the outlet is approximately 163…200 ppm. The main factor and parameter directly affecting surface slagging is the maximum local flame temperature (combustion core temperature) t_{max}, considered in relation to the ash melting characteristics of the specific fuel.

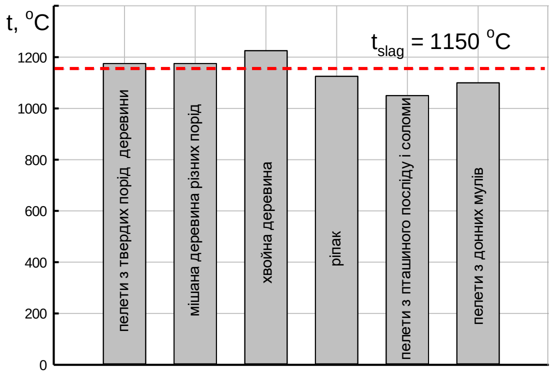

Fig. 9. Comparative analysis of maximum flame temperatures based on CFD modeling data with the critical ash slagging threshold for renewable fuels (the dashed line indicates the boundary of the safe window at 1150 °C).

Fig. 9 clearly shows that for wood pellets (hardwood, mixed wood, and softwood), the flame temperature (1175…1225 °C), although being the highest among the considered cases, does not exceed or is close to the safe melting threshold of wood ash (1200…1250 °C). For agro-pellets (rapeseed, straw, and sludge), the ash deformation threshold is significantly lower (≈ 1100 °C); however, due to «soft combustion» and staged air supply in the solid-fuel boiler, the actual temperature is maintained at 1050…1125 °C, which also prevents deposit formation and boiler fouling.

CONCLUSIONS

Based on the conducted CFD modeling of the thermochemical conversion processes of various types of renewable biomass in the combustion chamber of a shaft-type solid-fuel boiler, the following scientific and practical results have been formulated:

1. The regularities of the influence of intensive aerodynamic turbulence on the macrokinetics of burnout of high-density fuel pellets (made from hardwood species) have been established. It has been proven that the formation of vortex structures in the lower part of the shaft compensates for the initial kinetic retardation of the thermal decomposition of the dense char residue of oak and beech. This increases the residence time of the dispersed phase in the high-temperature zone, ensuring stable thermal output and achieving a particle burnout degree (Particle Burnout) of 98.5–99.0% with minimal thermal impact on the heat transfer surfaces.

2. The features of staged combustion of mixed wood from different species conglomerates have been determined. It has been established that vortex mixing provides spatial homogenization of the temperature field within the range of 1100…1250 °C. This temperature level is thermodynamically optimal for the complete destruction of tars and heavy hydrocarbons of hardwood species; however, it does not reach the temperature threshold for intensive generation of thermal nitrogen oxides, confirming the stability of the flame geometry and the stability of the flame front.

3. The thermal profile of the flame during the combustion of softwood biomass has been determined, characterized by a shift of the maximum heat release zone (the core with temperatures of 1150…1300 °C) directly toward the burner outlet due to the high rate of devolatilization of resinous compounds. It has been mathematically confirmed that the organized balance of air supply component flow rates ensures radiative flame uniformity and minimizes the local erosive and corrosive aggressiveness of flue gases toward metallic heat transfer surfaces.

4. The effectiveness of the «soft combustion» concept for high-calorific agro-pellets (rapeseed), which are prone to low-temperature slagging, has been substantiated. It has been numerically demonstrated that precise regulation of staged air supply makes it possible to stabilize local temperatures within the furnace volume in the range of 1050…1200 °C. This maintains the thermal regime strictly below the critical threshold of rapeseed ash deformation and melting, preventing the phase transition of ash deposits into glassy slag on the grates while maintaining carbon burnout completeness at the level of 97…98%.

5. The possibility of effective utilization of high-ash and high-nitrogen alternative substrates (pellets made from poultry manure, straw, and bottom sludge) has been mathematically proven. It has been established that, due to the ballast damping effect of the mineral fraction of sludge and the high volatile matter release from straw, an extended thermochemical conversion zone is formed with local temperatures maintained within the «safe window» (1000…1150 °C), which is below the sludge sintering temperature. At the

same time, the formation of a reducing environment (0…36 ppm NO_x at the flame root) and staged oxidizer supply ensure the binding of fuel-bound nitrogen, stabilizing the integral outlet NO_x concentrations within the range of 145…218 ppm, which fully complies with the environmental requirements of Directive 2010/75/EU without the use of catalytic denitrification systems.

References

[1] Kinefuchi E. Burning forests: the wood pellet industry's framing of sustainability and its shadow places. Frontiers in Communication, 2024, vol. 9, art. 1237141. doi: 10.3389/fcomm.2024.1237141.

[2] Kang S.B., Sim B.S., Kim J.J. Volume and Mass Measurement of a Burning Wood Pellet by Image Processing. Energies, 2017, vol. 10, no. 5, art. 603. doi: 10.3390/en10050603.

[3] Kang S.B., Kim J.J., Choi K.S., Sim B.S., Oh H.Y. Development of a test facility to evaluate performance of a domestic wood pellet boiler. Renewable Energy, 2013, vol. 54, pp. 2-7. doi: 10.1016/j.renene.2012.11.007.

[4] Zhovmir M.M. Carbon burnout from the char of a single cylindrical pellet. Energetika, 2023, vol. 68, no. 1, pp. 1-12. doi: 10.6001/energetika.v68i1.4852.

[5] Lysenko O.M., Veremiichuk H.M., Siryi O.A. [Research of burning of agricultural pellets in boilers with capacity up to 25 kW]. Thermophysics and Thermal Power Engineering, 2022, vol. 44, no. 3, pp. 99-108. doi: 10.31472/ttpe.3.2022.10. (In Ukrainian).

[6] Ahn J., Kim H.J. Combustion Process of a Korean Wood Pellet at a Low Temperature. Renewable Energy, 2019, vol. 145, pp. 1361-1369. doi: 10.1016/j.renene.2019.05.031.

[7] Vershinina K.Y., Dorokhov V.V., Romanov D.S., Strizhak P.A. Combustion stages of waste-derived blends burned as pellets, layers, and droplets of slurry. Energy, 2022, vol. 251, art. 123897. doi: 10.1016/j.energy.2022.123897.

[8] Polonini L.F., Petrocelli D., Parmigiani S.P., Lezzi A. Experimental study of PM emissions from wood pellet stoves with an innovative burning pot. Journal of Physics: Conference Series, 2019, vol. 1224, no. 1, art. 012018. doi: 10.1088/1742-6596/1224/1/012018.

[9] Silva S.B., Donária M., Kerller J., Andrade C.R., Carneiro A.C.O., Protásio T.P. Influence of physical and chemical compositions on the properties and energy use of lignocellulosic biomass pellets in Brazil. Renewable Energy, 2019, vol. 147, pp. 1870-1879. doi: 10.1016/j.renene.2019.09.131.

[10] Brand M.A., Jacinto R.C., Cunha A. [Qualidade de pellets de galhos secos de araucária e partículas de pinus] [Quality of pellets from dry branches of araucaria and pine particles]. Energia na Agricultura, 2019, vol. 33, no. 4, pp. 303-312. doi: 10.17224/EnergAgric.2018v33n4p303-312. (In Portuguese).

[11] Ojczyk Grzegorz, Wiesław Zima. 2017. „Stanowisko badawcze ko-tłów stałopalnych małej mocy oraz kolektorów słonecznych". Cie-płownictwo, Ogrzewnictwo, Wentylacja, 48 (7): 281-286.

[12] Brand M.A., Rodrigues T., Silva J.P., Oliveira J. Recovery of agricultural and wood wastes: The effect of biomass blends on the quality of pellets. Fuel, 2021, vol. 284, art. 118881. doi: 10.1016/j.fuel.2020.118881.

[13] Strandberg A., Thyrel M., Skoglund N., Lestander T.A., Broström M., Backman R. Biomass pellet combustion: Cavities and ash formation characterized by synchrotron X-ray micro-tomography. Fuel Processing Technology, 2018, vol. 176, pp. 110-117. doi: 10.1016/j.fuproc.2018.03.023.

[14] Novčić Đ., Nikolić M., Karamarković R., Šimunović D. [Gradual combustion of wood logs by the use of preheated air]. Proc. 10th Int. Conf. "Heavy Machinery-HM 2021", Vrnjačka Banja, 2021.

[15] Karamarković R., Novčić Đ., Lazarević A., Nikolić M. [Experimental Investigation of an 18-kW-Wood-Log-Fired Gasification Boiler]. Proc. 9th Conf. on Thermal Science and Engineering of Serbia, Sokobanja, 2019.

[16] Pelka G., Jach-Nocoń M., Paprocki M. et al. Comparison of Emissions and Efficiency of Two Types of Burners When Burning Wood Pellets from Different Suppliers. Energies, 2023, vol. 16, no. 4, art. 1695. doi: 10.3390/en16041695.

[17] Kang S.B., Kim J.J., Choi K.S., Sim B.S., Oh H.Y. Development of a test facility to evaluate performance of a domestic wood pellet boiler. Renewable Energy, 2013, vol. 54, pp. 2-7. doi: 10.1016/j.renene.2012.11.007.

[18] Priestley M., Kong X., Pei X. et al. Pros and cons of wood and pellet stoves for residential heating from an emissions perspective. Environmental Sci-ence: Atmospheres, 2023, vol. 3, no. 4, pp. 711-726. doi: 10.1039/D2EA00022A

[19] Ciupek B., Urbaniak R., Judt W. [Experimental Research of Changes in CO, NOx and PM Concentrations in Flue Gases During Combustion of Wood Pellets With Wheat Seeds]. Ciepłownictwo, Ogrzewnictwo, Wentylacja, 2019, vol. 50, no. 2, pp. 56-61. doi: 10.15199/9.2019.2.3. (In Polish).

[20] Kjällstrand J., Perzon M. Chimney emissions from small-scale burning of pellets and fuelwood. Biomass and Bioenergy, 2004, vol. 27, no. 6, pp. 557-561. doi: 10.1016/j.biombioe.2003.08.014.

[21] Siaudinis G., Jasinskas A., Šarauskis E., Skuodienė R., Repšienė R., Karcauskiene D. The Influence of Lime Material and Nitrogen Fertilization on Reed Canary Grass Productivity,

Plant Quality and Environmental Impact of Using Biomass for Energy Purposes. Agronomy, 2021, vol. 11, no. 5, art. 895. doi: 10.3390/agronomy11050895.
[22] Jasinskas A., Minajeva A., Šarauskis E., Romaneckas K., Kimbirauskienė R., Pedišius N. Recycling and utilisation of faba bean harvesting and threshing waste for bioenergy. Renewable Energy, 2020, vol. 162, pp. 1967-1978. doi: 10.1016/j.renene.2020.08.070.
[23] Kim D.Y., Han Y.H., Choi M.A., Park S.K., Jang Y.K. [A Study on Estimation of Air Pollutants Emission from Wood Stove and Boiler, Wood-pellet Stove and Boiler]. Journal of Korean Society for Atmospheric Environment, 2014, vol. 30, no. 3, pp. 251-260. doi: 10.5572/KOSAE.2014.30.3.251. (In Korean).
[24] ANSYS FLUENT 14.5 Theory Guide. New-York, USA, ANSYS Inc, 2012.
[25] Baraniuk O.V., Vorobiov M.V., Rachynskyi A.Yu. CFD-modeliuvannia protsesiv teploobminu i hidrodynamiky zasobamy prohramnoho kompleksu: monohrafiia [CFD modeling of heat transfer and hydrodynamics processes by means of a software package: monograph]. Kyiv, KPI im. Ihoria Sikorskoho, Vyd-vo «Politekhnika», 2023. 164 p.
[26] Basok B., Veremiichuk A., Baranyuk O., Siryi O. Simulation of biopellet combustion process in low power boilers. Proc. 5th Int. Sci.-Tech. Conf. “Actual Problems of Renewable Energy, Construction and Environmental Engineering”, Kielce, 2021, pp. 141-144.
[27] N. Striūgas, B. Soroka, K. Zakarauskas, N. Vorobyov. Thermodynamic analysis and experimental tests of wood waste gasification and combustion plants. 11-th International Research and Practical Conference Coal heat power industry: rehabilitation and development problems September, 16-20, 2015, Kiev, Ukraine.

Information about authors.

Rachynskyi Artur
Associate Professor, Department of Thermal and Alternative Energy Engineering. Research interests: experimental studies of processes in energy equipment.
ORCID: 0009-0006-2120-5541
E-mail: arturrachinskiy@gmail.com

Chernousenko Olga
Professor, Department of Thermal and Alternative Energy Engineering.
Research interests: hydrodynamics and heat and mass transfer in gas–droplet systems. ORCID 0000-0002-1427-8068
E-mail: chernousenko20a@gmail.com

Tkachenko Svitlana
Senior lecturer, Educational and Research Institute of Aerospace Technologies. Research interests: mechanisms, drives, machine components, modeling, design, CAD/CAE systems, sensors, instrumentation.
ORCID: 0000-0002-6747-5698
E-mail: svittkachenko8@gmail.com

Baranyuk Oleksandr,
Associate Professor, Department of Thermal and Alternative Energy Engineering. Research interests: numerical modeling of processes in power equipment.
ORCID: 0000-0001-6008-6465
E-mail: AleksandrW@i.ua

Onysko Andrii
Associate Professor, Department of Digital Technologies in Energy. Research interests: development of digital twins for energy equipment.
ORCID: 0000-0001-7178-1417
E-mail: oniskoandrij2020@gmail.com