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Development of a biomass-fueled boiler for grain drying applications

H. Lapenko | O. Gorbenko | T. Lapenko | S. Kolotii

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Correspondence Author
O. Gorbenko
E-mail:
oleksandr.gorbenko@pdau.edu.ua

Poltava State Agrarian University,
Skovoroda Str., 1/3,
Poltava, 36000, Ukraine

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The article presents the results of research and development of an energy-efficient biomass-fired boiler designed for grain drying using locally available types of biomass as an alternative energy source. The relevance of implementing bioenergy technologies in agricultural production is substantiated, taking into account the rising cost of fossil fuels and the growing need for environmental sustainability in the agrarian sector. A comparative analysis of modern grain dryers has been conducted, highlighting their design features, advantages, and limitations in the context of biomass utilization. A boiler design has been developed, incorporating a two-section tubular recuperative heat exchanger, an automated fuel feeding system, and a multi-stage fan-driven air circulation mechanism. A distinctive feature of the proposed model is the use of high-temperature-resistant AISI 310S stainless steel in the combustion chamber, which ensures increased resistance to thermal stress, slag formation, and soot buildup. An air recirculation system for the drying chamber is also proposed to enhance the overall energy efficiency. Based on the proposed design, experimental thermal modeling was carried out. The results were generalized as temperature dependencies under various biomass feed rates. The obtained graphs and tabulated data confirm the system's predictable response to parameter changes, which is critical for automated process control and achieving high-quality grain treatment. Mathematical modeling of thermal regimes confirmed a high degree of correlation (R = 0.95) between the biomass feed rate and the temperature of air supplied to the dryer, as well as operational stability across a wide load range. The findings indicate that implementing such a boiler in agricultural practice can significantly reduce energy consumption, lower harmful emissions, and improve the autonomy of farming enterprises. The proposed technical solution offers a promising direction for modernizing grain drying equipment under current agricultural production conditions.

Keywords: biomass boiler, grain drying, biomass, grain dryer, energy efficiency.

Розробка біопаливного котла для сушіння зерна з використанням біомаси

Г. О. Лапенко | О. В. Горбенко | Т. Г. Лапенко | С. Ю. Колотій

Полтавський державний аграрний університет,
м. Полтава, Україна

У статті представлено результати дослідження та розробки енергоефективного біопаливного котла, призначеного для сушіння зерна із застосуванням місцевих видів біомаси, як альтернативного джерела енергії. Обґрунтовано актуальність впровадження біоенергетичних технологій у сільськогосподарське виробництво з огляду на зростання цін на викопні енергоносії та потребу в екологізації аграрної сфери. Проведено порівняльний аналіз сучасних зерносушильних установок, визначено їх конструктивні особливості, переваги та обмеження при використанні біопалива. Розроблено конструкцію біопаливного котла з двосекційним трубчастим рекуперативним теплообмінником, системою автоматизованої подачі палива та багатоступеневим вентиляторним забезпеченням циркуляції повітря. Особливістю запропонованої моделі є використання жароміцної нержавіючої сталі AISI 310S у топковому відділенні, що забезпечує підвищену стійкість до теплових навантажень, шлакоутворення та сажових відкладень. Запропоновано схему з рециркуляцією сушильного повітря для підвищення енергоефективності процесу. На базі розробленої системи було виконано експериментальне моделювання теплових режимів, результати якого узагальнено у вигляді температурних залежностей для різних режимів подачі біопалива. Графіки та табличні дані свідчать про передбачувану реакцію системи на зміну параметрів, що є критично важливим для автоматизованого управління сушильним процесом та досягнення високої якості обробки зерна. Математичне моделювання температурних режимів підтвердило високий ступінь кореляції між кількістю поданого біопалива та температурою повітря, що надходить до сушильної установки (R = 0,95), а також стабільність роботи системи в широкому діапазоні навантажень. Результати аналізу демонструють, що впровадження такого котла у виробничу практику дозволяє знизити енергоспоживання, зменшити шкідливі викиди в атмосферу та підвищити рівень автономності аграрного підприємства. Запропоноване технічне рішення є перспективним напрямом модернізації зерносушильного обладнання в умовах сучасного агровиробництва.

Ключові слова: біопаливний котел, сушіння зерна, біомаса, зерносушарка, енергоефективність.

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Introduction

In the current context of a global energy crisis and increasing environmental pressure, the use of renewable energy sources, particularly biomass, is gaining special relevance. Biomass is considered one of the most promising types of environmentally friendly fuel [1, 2], enabling a reduction in dependence on fossil energy sources and a significant decrease in greenhouse gas emissions. The use of biofuels in the agricultural sector, especially for grain drying [3–5], creates opportunities to improve the energy efficiency of agricultural production.

The issue of developing effective biomass-based energy systems for agricultural needs is actively explored in global scientific literature. Researchers from the EU, USA, China, and India are devoting considerable attention to the creation of high-efficiency biomass boilers adapted to local raw materials and capable of providing stable thermal and energy support for agricultural processes.

In works [6, 7], the author considers biomass as a universal energy source, paying particular attention to its thermochemical properties, availability, and potential to replace fossil fuels. The study systematizes data on various types of biomass, including agricultural residues, wood, and energy crops, analyzing their calorific value, moisture content, and other parameters that influence combustion efficiency. The importance of adapting combustion technologies to specific types of biomass is also emphasized, taking into account their physicochemical characteristics. This analysis supports the conclusion that effective biomass utilization requires the development of specialized boilers capable of providing stable combustion with minimal emissions. In the context of grain drying, these findings are highly relevant, as they offer a theoretical foundation for selecting appropriate biomass types and determining optimal conditions for their application in energy systems.

A series of scientific works [8, 9] provides a detailed analysis of various biomass-to-energy conversion methods, including thermochemical and biochemical processes. The author explores the advantages and limitations of each approach, as well as their suitability for different biomass types. Special emphasis is placed on the importance of biomass pretreatment, such as drying and grinding, to ensure efficient combustion. The necessity of developing systems that can adapt to the variable properties of biomass is also highlighted, which is particularly relevant for agricultural residues.

In work [10], the operating principle and design features of circulating fluidized bed (CFB) boilers are described in detail. These boilers are characterized by high combustion efficiency and the ability to operate with various types of fuel, including biomass. This technology enables a uniform temperature distribution within the combustion zone, promoting complete fuel combustion and reducing harmful emissions. The author also notes that CFB boilers offer high flexibility in fuel selection, which is a significant advantage when utilizing diverse types of biomass. Consequently, this can ensure a stable and efficient heat supply by using locally available agricultural residues as fuel.

One of the key technical challenges associated with biomass combustion in boilers is slagging, the formation and accumulation of solid deposits on combustion and heat exchange surfaces. This phenomenon is caused by the high content of ash, potassium, chlorine, and silicon in many types of biomass, particularly in agricultural residues such as straw, husks, or branches. At high temperatures, these elements react to form molten and agglomerated ash particles, which result in slag build-up.

Studies [11–13] emphasize that slagging not only reduces the thermal efficiency of boilers but also leads to equipment damage, shorter maintenance intervals, and increased operational costs. These works examine the mineralogical composition of biomass ash and demonstrate that the ash melting temperature is a critical parameter for assessing slagging risks.

Modern approaches to addressing the problem include optimizing the design of the furnace section, applying additives that increase ash melting temperatures, and pre-treating biomass to reduce the content of aggressive elements. The issue of slag formation is especially relevant for small-scale boilers used in agriculture, as they often have limited capabilities for automatic cleaning of heat exchange surfaces.

Currently, the domestic agricultural sector, especially under conditions of constantly rising energy prices and the decentralization of energy supply, requires the implementation of innovative solutions to ensure the energy independence of farming enterprises. Grain drying is a critical stage of post-harvest processing that requires significant energy input. The development of a biomass-fired boiler that efficiently utilizes locally available biomass can not only reduce energy costs but also create a closed-loop energy system within the farm.

Thus, the relevance of this study is driven by the need for energy-efficient, environmentally friendly, and economically viable technologies in the agricultural sector.

The aim of the study

The aim of this research is to design and justify the construction of a biomass boiler optimized for grain drying using accessible biomass as a fuel source.

Materials and methods

As part of this study, the authors conducted a comprehensive analysis of existing grain dryer designs, both domestic and international. The main focus was placed on techno-economic efficiency, energy consumption, and the potential for integrating alternative energy sources, particularly biomass. Based on the obtained data, the optimal type of drying equipment was selected to suit the conditions of the enterprise LLC “Agrotechservice” (Reshetylivka, Ukraine).

The outcome of the research was the development of a biomass boiler design adapted for efficient grain drying. The technical configuration of the boiler includes a combustion chamber with a grate made of heat-resistant AISI 310S steel, a system of screw conveyors for biomass feeding, a two-section recuperative tubular heat exchanger, forced-draft and air supply fans, a hot air recirculation system, and sensor-based control of thermal process parameters. The methodology involved experimental testing of the boiler under real agricultural production conditions using various biomass mixtures. The analysis of thermal performance made it possible to assess the impact of temperature fluctuations on heat transfer, slagging behavior, and the durability of the boiler's key structural components.

Results and discussion

According to the analysis [14–17], the core principle of grain drying involves heat supply, moisture migration from the inner layers of the grain to its surface, and subsequent removal of that moisture. Modular grain dryers that utilize the convective drying method have proven to be the most suitable for integration with biomass heat generators. In such systems, hot air or flue gases penetrate the intergranular space, intensifying the drying process.

Based on the technical assessment of existing equipment, an original biomass boiler design [18] was proposed to meet the needs of LLC "Agrotechservice" (Reshetylivka, Ukraine). A key factor in the system's efficiency is its ability to regulate the temperature of the flue gases and air supplied to the dryer in accordance with changes in biomass feed rate.

The proposed biomass boiler design (***Fig. 1***), intended for grain drying, implements a modern approach to the use of renewable energy sources. At its core is a combustion chamber (item 15), equipped with a grate containing air channels (item 14) and a frame made of heat-resistant austenitic stainless steel AISI 310S, which ensures long-term operation and resistance to high-temperature loads.

The biomass is fed from the hopper (item 11) using two screw conveyors (item 12), which transport the fuel directly into the combustion chamber. There, it is activated by air streams generated by fans (item 13) passing through the perforated base, ensuring uniform combustion.

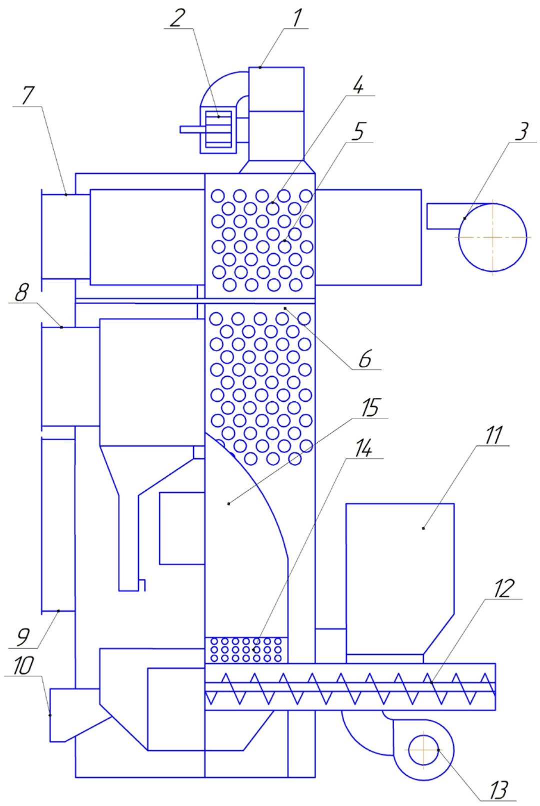

Fig. 1. Design of a biomass-fired boiler for grain drying

Above the combustion chamber, two heat exchange units are positioned – the upper section (item 4) and the lower section (item 6) – which together form a tubular recuperative system. Both sections consist of sets of seamless tubes (item 5) arranged in a staggered pattern to maximize heat transfer. The sections are connected in series via an air duct, enabling efficient thermal energy transfer from the flue gases.

To minimize heat losses, the outer surfaces of the heat exchanger are covered with thermal insulation. Exhaust gases are discharged through a flue (item 1) equipped with an extraction fan (item 2), which ensures stable gas removal.

The heat exchange system is enhanced by a bypass fan (item 3), which forces air into the inter-tubular space, where it is heated by the external tube surfaces and then delivered to the drying chamber via an air duct (item 7). The lower section of the heat exchanger also receives air from the recirculation channel (item 9), which originates from the dryer. This reduces the boiler load due to the preheated air.

For maintenance, the combustion chamber is equipped with convenient hinged doors (item 10) that provide access for cleaning and ash removal. Temperature control and heat exchange management are carried out using a modern sensor-based system and programmable electromechanical devices.

The biomass-fired boiler for grain drying operates in automatic mode, ensuring stable heat generation through regulated fuel and air supply. At the initial stage, an ignition mass of fuel is manually placed into the combustion chamber (item 15) to initiate the combustion process. Once stable combustion is achieved, the screw conveyors (item 12) and fans (item 13) are activated, continuously delivering biomass from the hopper (item 11) into the combustion zone.

Once inside the combustion chamber, the biomass is activated by air flows through the grates (item 14), where it undergoes phased combustion, generating thermal energy and flue gases. The combustion intensity and gas temperature are controlled by adjusting the amount of fuel and air supplied, allowing the thermal output to be tailored to the requirements of the drying process.

Temperature fluctuations caused by variations in biomass quality can create thermal stress on furnace components [19, 20]. However, the use of AISI 310S steel provides high heat resistance, resistance to soot deposition, and ensures the durability of the boiler structure.

Studies on structural steels, including domestic heat-resistant grades 10Kh23N18 and 20Kh23N18, as well as the low-carbon high-alloy chromium-nickel steel AISI 310S, have led to the following conclusions:

1. For the production of combustion chamber components in biomass-fired boilers operating under conditions of anticipated corrosion, it is advisable to use AISI 310S steel. According to ASTM A240, this steel contains approximately 26 % chromium, up to 22 % nickel, and no more than 0.03 % sulfur, which ensures the retention of mechanical strength at elevated temperatures. Additionally, this steel offers good weldability, and its recommended working temperature is up to 1000°C.

2. Compared to domestic steel grades, AISI 310S provides a longer service life and improved reliability of boiler components used for biomass combustion.

3. The conducted analysis of boiler elements confirmed the appropriateness of the selected material, while also minimizing the formation of carbon deposits on wall openings during operation.

Under the influence of forced airflow, the flue gases are directed through the flue channel to the lower section of the heat exchanger (item 6), where heat transfer occurs via contact with the inner walls of the tubes (item 5). The cooled gases are then directed to the upper section (item 4), which provides additional heat extraction.

Due to increased resistance within the heat exchange system, the velocity of gas flow decreases. To prevent stagnation zones, the extraction fan (item 2) is activated to discharge the gases through the chimney (item 1).

Simultaneously, air is forced into the inter-tubular space of the heat exchanger by fans (items 3 and 9), ensuring efficient heat transfer from the outer surfaces of the tubes and the furnace structure. The resulting hot air is delivered to the drying chamber through air ducts (items 7 and 8). After passing through the dryer, part of the heated air is returned via the recirculation channel (item 9) to the heat exchanger, reducing fuel consumption by reusing thermal energy.

Upon completion of the drying cycle, fuel supply is stopped, the fans are gradually shut down, and remaining fuel residues and ash deposits are removed via the access doors (item 10). If necessary, the grate is cleaned of soot to maintain high equipment efficiency.

Fig. 2 presents the results of temperature modeling during biomass combustion in the proposed boiler.

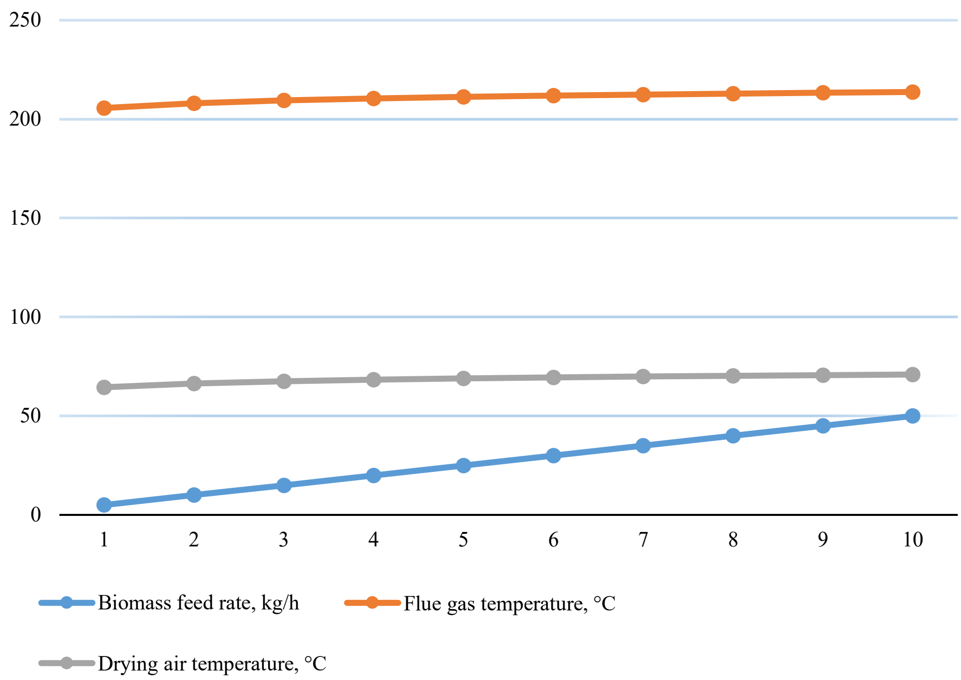

Fig. 2. Simulation results of temperatures during biomass combustion in the proposed boiler

To evaluate the performance efficiency of the biomass-fired boiler for grain drying, a mathematical analysis was conducted to determine the relationship between the temperature of the air supplied to the drying chamber and the intensity of biomass feed. The simulation results showed a clear upward trend in air temperature as the fuel feed rate increased. The average air temperature was 68,74 °C, and the median was 69,27 °C, indicating an approximately symmetrical distribution of temperature values. Temperature fluctuations ranged from 64,51 °C to 70,95 °C, demonstrating stable system operation with limited variability (standard deviation of only 2,05 °C).

The constructed linear regression model revealed a strong correlation between the variables: the correlation coefficient R was 0.95, indicating a very strong linear relationship between fuel feed rate and air temperature. A low p-value ($2{,}3\times10^{-5}$) confirms the statistical significance of this correlation. These findings demonstrate the reliability and predictability of the boiler's thermal performance, allowing precise control of the drying process and optimized fuel consumption according to technological requirements.

Conclusions

1. The study substantiates the feasibility of using biomass as an alternative energy source for grain drying equipment, significantly reducing the energy dependence of agricultural enterprises on traditional fossil fuels.
2. Based on a technical analysis of existing grain dryers, an innovative biomass boiler design with a tubular recuperative heat exchanger was developed. This design ensures efficient utilization of combustion heat and enables air recirculation.
3. The proposed system features automatic regulation of biomass and air supply, taking into account the temperature and humidity of the grain and the air environment, which ensures stable heat generation and adaptability of the drying process to changing conditions.
4. Mathematical modeling revealed a strong linear correlation ($R = 0.95$) between biomass feed rate and drying air temperature, confirming the effectiveness of thermal control in the system.
5. The use of heat-resistant steel (AISI 310S) in the design of the combustion chamber improves thermal stability, reduces the risk of deformation, and contributes to the long-term safe operation of the equipment.
6. The developed biomass boiler can be implemented in domestic agricultural practice as an effective, environmentally friendly, and economically viable solution for energy-efficient grain drying.

Prospects for further research include optimizing the geometric parameters of the heat exchanger to improve heat recovery efficiency. Future studies will also focus on slag formation processes for different biomass types to develop furnace designs resistant to aggressive environments. Additionally, the implementation of an intelligent control system based on real-time thermodynamic parameter forecasting is considered advisable.

Conflict of interest

The authors state that there is no conflict of interest.

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ORCID

H. Lapenko https://orcid.org/0000-0003-1435-5307
O. Gorbenko https://orcid.org/0000-0003-2473-0801
T. Lapenko https://orcid.org/0000-0001-8055-6698
S. Kolotii https://orcid.org/0009-0002-1768-3111