ТЕХНІЧНІ НАУКИ

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CONSTRUCTIVE AND ENGINEERING SOLUTIONS FOR A TOP-COMBUSTION SOLID-FUEL BOILER FOR LOCAL HEATING SYSTEMS

Abstract

The paper considers constructive and engineering solutions for a top-combustion solid-fuel boiler intended for use in local heating systems. The operating principle of long-burning candle-type boilers is analysed, and their main structural features are generalised. Based on this analysis, a solid-fuel boiler design is proposed that is focused on simplified manufacturing, the use of readily available materials, and minimisation of the number of structural elements and welded joints.

A schematic representation of the boiler operating principle is presented, the main structural components are described, and the principal stages of manufacturing are outlined. The proposed design incorporates an upper air supply system with a movable distributor positioned above the fuel layer. This arrangement is intended to provide controlled air supply to the active combustion

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zone as the fuel charge is gradually consumed. An internal screen separates the zone of gaseous product formation from the main heat-exchange volume and creates conditions for combustion of gaseous products of thermal decomposition. Tubular heat-exchange elements are arranged in the flow path of hot combustion products to facilitate heat transfer to the heat carrier.

A preliminary assessment of the energy potential of the proposed boiler is performed based on the lower heating value and mass of the firewood charge. The obtained relationships connect the fuel load, its energy potential, and the expected operating duration at a single fuel load. The calculated estimates are considered preliminary, since the actual useful heat output, thermal efficiency, fuel consumption rate, flue gas temperature, and other heat-balance parameters require experimental determination. The proposed design may represent a technically feasible alternative to commercially manufactured long-burning boilers for local heating systems, subject to further experimental validation of its thermal performance and operating characteristics.

Key words: *solid fuel boiler, top combustion, biomass, firewood fuel, local heating systems, simplified manufacturing.*

Introduction. In the current context of rising energy costs, decentralization of heat supply systems, and increasing risks of disruption to centralized energy infrastructure, the use of local solid-fuel-based heat sources is becoming particularly relevant. For Ukraine, this issue has gained additional importance due to damage to energy infrastructure facilities and the need to ensure reliable heat supply to consumers under crisis and emergency conditions [4].

Solid-fuel boilers remain among the most versatile and accessible means of heat generation, as they allow the use of a wide range of fuels, including firewood, wood waste, and other types of biomass [1; 5; 13]. At the same time, a significant proportion of modern heat-generating units are characterized by complex designs, automated combustion control systems, and increased requirements for fuel quality, which complicates their manufacturing, operation, and maintenance under conditions of limited resources [7].

One promising direction for improving solid-fuel boilers is the implementation of the top-combustion principle, in which the combustion process is localized in the upper fuel layer, and air is supplied directly to the active combustion zone. This approach is expected to provide a more uniform combustion process, reduce heat losses with flue gases, and enable long-term operation of the boiler on a single fuel load [6; 9; 17].

Top-combustion design solutions have been practically implemented in shaft-type boilers, including well-known long-burning designs that have demonstrated acceptable operational performance with relative structural simplicity [12]. However, further reduction of material consumption, the number of structural elements, and manufacturing time of such boilers remains a relevant scientific and practical task.

A significant contribution to the study of biomass energy utilization, including its thermal pre-treatment, torrefaction, and combustion processes, has been made in the authors' previous works [2; 14–16; 18]. The obtained results confirm the feasibility of using plant biomass and its thermally treated products in local heat supply systems and provide a scientific and practical basis for improving solid-fuel thermal installations.

In this context, the development of structural and engineering solutions for a top-combustion solid-fuel boiler designed for stable operation on firewood, reduced structural complexity, and the possibility of manufacturing from readily available materials for use in local heat supply systems is of particular relevance.

The aim of this study is to develop and substantiate the design of a top-combustion solid-fuel boiler that is intended to provide long-term operation on a single fuel load, stable formation and combustion of gaseous products of thermal decomposition, and simplified manufacturing and operation under the conditions of local heat supply systems.

To achieve this purpose, the following objectives were defined:

– to analyze the structural features of top-combustion and fuel-gasification solid-fuel boilers;
– to substantiate the conceptual design of a boiler with separation of producer gas formation and combustion zones;
– to develop an air supply system design with an upper distributor and a two-section structure;
– to determine the main geometric parameters of the boiler and the relative arrangement of its elements;
– to assess the feasibility of applying the proposed design for firewood fuel in local heat supply systems.

Presentation of the main research material. The research was conducted at the Educational and Research Laboratory "DAK GPS" of Higher Educational Institution "Podillia State University", whose scientific activities are focused on the study of biomass thermal processing and energy utilization processes, as well as the improvement of solid-fuel thermal installations [3; 10; 19].

The object of the study is a shaft-type top-combustion solid-fuel boiler designed to operate on firewood. The subject of the study is the boiler's structural solutions that determine air supply conditions, combustion zone formation, and the duration of operation on a single fuel load.

An analysis of modern long-burning solid-fuel boilers shows that the most widespread designs implement the top-combustion principle with air supplied to the upper zone of the fuel shaft. Such boilers are characterized by fuel placement beneath the air distributor and the formation of a stable combustion front that gradually moves downward along the height of the fuel charge.

During operation of boilers of this type, two functional zones are distinguished: the zone of gaseous product formation in the upper fuel layer and the zone of their combustion located directly above the fuel conversion zone. This configuration is expected to support long-term boiler operation on a single fuel load and contribute to more uniform heat release.

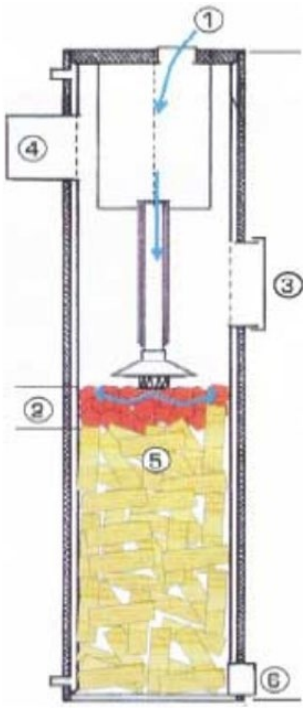


Fig. 1. Generalized schematic diagram of the operating principle of a top-combustion solid-fuel boiler [9]: 1 – air circulation; 2 – combustion zone; 3 – loading door; 4 – chimney; 5 – furnace chamber; 6 – ash-cleaning opening

Based on the analysis of existing technical solutions, a design of a top-combustion solid-fuel boiler adapted to the conditions of local heat supply systems and simplified manufacturing has been developed. The conceptual diagram of the proposed boiler is shown in Fig. 2.

The boiler design (Fig. 2) incorporates a cylindrical shell with a sealed bottom and an upper cover, ensuring convenient fuel loading. Air is supplied to the combustion zone through a telescopic distributor located directly above the fuel layer and moving downward as the fuel burns out. The fuel is placed below the active combustion and thermal conversion zone, which corresponds to the operating principle of top-combustion boilers.

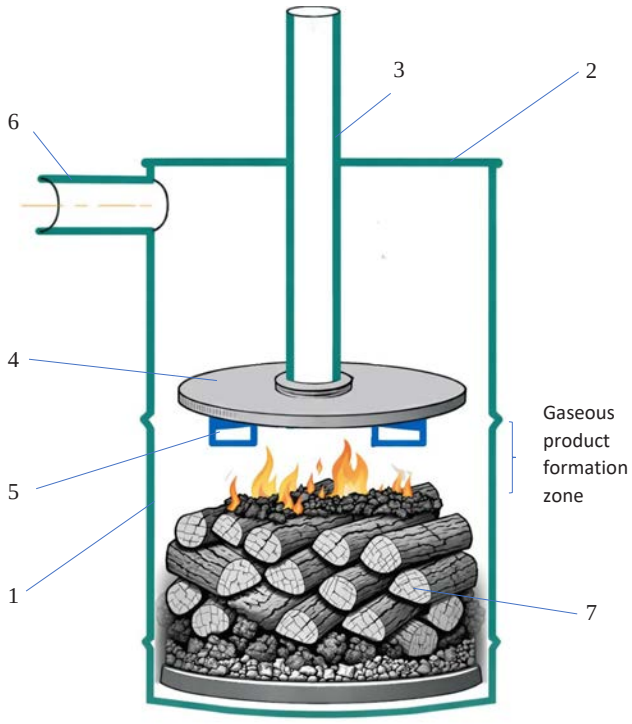


Fig. 2. Schematic diagram of the top-combustion solid-fuel boiler: 1 – body; 2 – cover; 3 – air supply nozzle; 4 – internal screen; 5 – screen support elements; 6 – flue gas outlet nozzle; 7 – fuel

The removal of combustion products is carried out through a flue gas outlet nozzle located in the upper part of the boiler. Heat exchange between hot gases and the heat carrier is implemented through a system of tubular elements integrated into the boiler shell. This design solution is intended to reduce the number of welded joints and simplify the boiler manufacturing technology.

The manufacturing technology of the proposed solid-fuel boiler is characterized by a minimal number of production operations and does not require complex specialized equipment. The main stages of boiler fabrication are shown in Fig. 3.

The manufacturing process of the solid-fuel boiler is based on a standard cylindrical steel blank used as the body of the product. At the initial stage, the welded seam is removed from the end part of the blank, resulting in the formation of a cylindrical boiler body with a sealed bottom without through gaps (Fig. 3a).

In the upper part of the body, an opening is made for connecting the flue gas outlet nozzle. A steel nozzle with a diameter of 150 mm is welded to the prepared opening, ensuring the removal of combustion products from the boiler chamber (Fig. 3b).



Fig. 3. Main stages of manufacturing the solid-fuel boiler:
a – formation of the body with a sealed bottom; b – installation of the flue gas outlet nozzle;
c, d – installation of air supply and heat exchange elements; e, f – final assembly of the boiler

The internal screen is manufactured in the form of a steel disk whose diameter is several centimeters smaller than the internal diameter of the body. In the central part of the screen, an opening is formed, to which a tubular element with a diameter of 100 mm is welded, designed for supplying air to the combustion zone (Fig. 3c). Such a design is intended to provide more uniform air distribution above the fuel surface.

A supporting element in the form of a steel profile with a height of 50–60 mm is installed on the lower side of the internal screen, ensuring stable positioning of the screen and formation of the required gap for the passage of producer gas (Fig. 3d).

At the final stage, the upper cover of the boiler is mounted, after which the structure is considered assembled and ready for operation. The proposed technological process is relatively simple to implement and involves a limited number of production operations, which may contribute to reduced manufacturing time and production costs.



Fig. 4. General view of the manufactured top-combustion boiler

For a preliminary quantitative assessment of the energy potential of the proposed design, the thermal transformations occurring during the sequential formation and combustion of gaseous products of fuel thermal conversion were considered. Unlike direct fuel combustion, in the proposed scheme, part of the heat is consumed for heating the fuel, evaporating moisture, and proceeding with endothermic gasification reactions. Therefore, the assessment of thermal efficiency should be performed taking into account the overall heat balance.

The total energy potential of the loaded batch of firewood is determined by the following relationship:

$$Q_{\text{p}} = m_p \, Q_{\text{n}}$$

where Q_p – the heat contained in the loaded fuel, MJ;
m_p – the mass of the loaded firewood, kg;
Q_n – the lower heating value of firewood, MJ/kg.

The actual value of Q_n depends on the fuel moisture content; therefore, this parameter should be taken into account when assessing the energy characteristics of the boiler.

For assessing the energy potential of firewood fuel, its heating value is an important parameter. For dry wood, the literature reports values in the range of 17–21 MJ/kg, while the actual value depends on the wood species, moisture content, and fuel composition [11]. For wood pellets with a moisture content of approximately 10%, an experimentally determined higher heating value of 19.53 MJ/kg has been reported [8]. This value can be used as a reference value for a preliminary assessment of the energy potential of solid woody biomass in the proposed boiler.

For the proposed design, these considerations are of particular importance because the internal screen forms a separate zone for the passage and combustion of producer gas, while the heat-exchange surfaces are located along the path of hot combustion products. Thus, the design creates conditions for utilizing heat not only from the direct combustion of wood but also from the gaseous products of its thermal conversion.

The operating duration of the boiler on a single fuel load can be estimated using the following relationship:

$$\tau = \frac{m_p}{B}$$

where τ – the operating duration on a single fuel load, h;
m_p – the mass of the loaded fuel, kg;
B – the average fuel consumption rate, kg/h.

An increase in the fuel load, combined with limiting the fuel burnout rate, directly affects the operating duration of the boiler.

The above relationships make it possible to relate the mass of the fuel load to its energy potential and the operating duration of the boiler. At the same time, the obtained relationships are of a calculated nature, while the final determination of the useful heat output and thermal efficiency requires experimental determination of the fuel consumption rate, inlet and outlet heat-carrier temperatures, flue gas temperature, and other heat-balance parameters.

The proposed design of the top-combustion solid-fuel boiler creates preconditions for stable and controllable operation in a long-duration combustion mode. Placement of the fuel under the air distributor and top air supply ensures the

formation of a localized gasification zone that gradually moves downward as the fuel burns out. This operating principle contributes to the reduction of peak thermal loads and more uniform heat release over time.

The use of an internal screen makes it possible to separate the producer gas formation zone from the main heat exchange volume, creating conditions for more complete combustion of volatile fuel components. The presence of tubular elements in the hot gas flow zone is expected to enhance heat transfer to the heat carrier without significantly complicating the overall design.

From an engineering perspective, an important feature of the boiler is the minimization of structural elements and welded joints, which may reduce the probability of loss of tightness and contribute to improved operational reliability. The simplicity of the geometry of the main units is expected to facilitate design reproducibility during manufacturing and reduce dependence on specialized production equipment.

The scientific contribution of the authors lies in the comprehensive integration of the top-combustion principle with structural solutions aimed at simplified manufacturing and adaptation of the boiler to the conditions of local heat supply systems. The proposed approach suggests that the developed design may represent a technically feasible alternative to commercially manufactured long-burning boilers, subject to further experimental validation of its thermal performance.

Conclusions.

1. A design of a top-combustion solid-fuel boiler intended for use in local heat supply systems and adapted for simplified manufacturing has been developed.
2. It has been shown that the application of top air supply and placement of fuel beneath the active thermal conversion zone create conditions for stable long-duration combustion and uniform heat release over time.
3. The proposed design solution with an internal screen and tubular heat exchange elements is expected to enhance heat transfer without significantly complicating the overall boiler design.
4. The developed manufacturing technology is characterized by a minimal number of operations and does not require specialized equipment, which may contribute to reducing production time and material costs.
5. The engineering novelty of the work lies in combining the top-combustion principle with structural solutions aimed at increasing manufacturability and reproducibility of the boiler design.
6. The obtained results indicate the feasibility of further experimental studies of the thermal performance of the proposed design and its potential practical application as an alternative to commercially manufactured long-burning boilers.

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КОНСТРУКТИВНІ ТА ІНЖЕНЕРНІ РІШЕННЯ ТВЕРДОПАЛИВНОГО КОТЛА З ВЕРХНІМ ГОРІННЯМ ДЛЯ ЛОКАЛЬНИХ СИСТЕМ ТЕПЛОПОСТАЧАННЯ

Анотація

У статті розглянуто конструктивні та інженерні рішення твердопаливного котла з верхнім горінням, призначеного для використання в локальних системах теплопостачання. Проаналізовано принцип роботи котлів тривалого горіння свічкового типу та узагальнено їх основні конструктивні особливості. На основі проведеного аналізу запропоновано конструкцію твердопаливного котла, орієнтовану на спрощення виготовлення, використання доступних матеріалів та мінімізацію кількості конструктивних елементів і зварних з'єднань.

Наведено схематичне представлення принципу роботи котла, описано основні конструктивні компоненти та окреслено основні етапи його виготовлення. Запропонована конструкція передбачає систему верхньої подачі повітря з рухомим розподільником, розташованим над шаром палива. Таке рішення призначене для забезпечення контрольованої подачі повітря до активної зони горіння в міру поступового вигоряння паливної закладки. Внутрішній екран відокремлює зону утворення газоподібних продуктів від основного теплообмінного об'єму та створює умови для спалювання газоподібних продуктів термічного розкладання. Трубчасті теплообмінні елементи розташовані на шляху руху гарячих продуктів згоряння для сприяння передачі теплоти теплоносію.

Проведено попередню оцінку енергетичного потенціалу запропонованого котла на основі нижчої теплоти згоряння та маси завантажених дров. Отримані залежності пов'язують масу паливної закладки, її енергетичний потенціал та очікувану тривалість роботи котла на одній закладці палива. Розрахункові оцінки розглядаються як попередні, оскільки фактична корисна теплова потужність, коефіцієнт корисної дії, витрата палива, температура відхідних газів та інші параметри теплового балансу потребують експериментального визначення. Запропонована конструкція може розглядатися як технічно доцільна альтернатива серійним котлам тривалого горіння для локальних систем теплопостачання за умови подальшої експериментальної перевірки її теплотехнічних характеристик та експлуатаційних параметрів.

Ключові слова: *твердопаливний котел, верхнє горіння, біомаса, дров'яне паливо, локальні системи теплопостачання, спрощене виготовлення.*

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