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DEVELOPMENT AND PARAMETER JUSTIFICATION OF A COMBINED PYROLYSIS-BASED GREENHOUSE HEATING SYSTEM

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Abstract. Introduction. *The high cost of agricultural products grown in modern greenhouse complexes is primarily associated with the significant share of energy consumption. Therefore, the development of energy-efficient greenhouse systems based on the effective use of alternative energy sources is an important scientific and technical task.*

Methods and Materials. *In this study, experimental and thermodynamic analysis methods were employed to develop a combined pyrolysis-based greenhouse heating system.*

Results. *As a result of the research, a combined pyrolysis-based greenhouse heating system was developed, and its parameters were substantiated. The proposed system enables biomass drying, production of pyrogas, liquid fuel, and biochar through the pyrolysis process, as well as the utilization of secondary heat from flue gases.*

Conclusion. *The proposed combined pyrolysis-based greenhouse heating system improves energy efficiency, reduces heat losses, and enables the production of alternative fuels. This system is of great importance for ensuring stable heat supply to greenhouses, utilizing local resources, and implementing environmentally friendly technologies.*

Keywords: *combined pyrolysis system, greenhouse heating, biomass, solar energy, pyrogas, biochar, heat recovery, alternative fuel, energy efficiency.*

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ISSIQXONALARNING KOMBINATSIYALASHGAN PIROLIZ QURILMALI ISITISH TIZIMINI ISHLAB CHIQISH VA PARAMETRLARINI ASOSLASH

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Annotatsiya. Kirish. *Zamonaviy issiqxona komplekslarida yetishtiriladigan mahsulotlar tannarxining yuqoriligi asosan energiya sarfining katta ulushi bilan bog‘liq. Shu sababli, muqobil energiya manbalaridan samarali foydalanishga asoslangan energiya tejamkor issiqxona tizimlarini ishlab chiqish muhim ilmiy-texnik vazifa hisoblanadi.*

Usul va materiallar. *Tadqiqot ishida kombinatsiyalashgan piroliz qurilmali issiqxona isitish tizimini ishlab chiqish uchun eksperimental va termodinamik tahlil usullaridan foydalanildi.*

Natijalar. *Tadqiqot natijasida issiqxonalarning kombinatsiyalashgan piroliz qurilmali isitish tizimi ishlab chiqildi va parametrlari asoslandi. Ushbu tizim yordamida biomassa quritish, piroliz jarayoni orqali pirogaz, suyuq yoqilg‘i va biochar olish hamda tutun gazlaridagi ikkilamchi issiqlikni utilizatsiya qilish imkoniyati yaratildi.*

Xulosa. *Taklif etilgan issiqxonaning kombinatsiyalashgan piroliz qurilmali isitish tizimi energiya samaradorligini oshirish, issiqlik yo'qotishlarini kamaytirish va muqobil yoqilg'i olish imkonini beradi. Ushbu tizim issiqxonalarni barqaror issiqlik bilan ta'minlash, mahalliy resurslardan foydalanish va ekologik toza texnologiyalarni joriy etishda muhim ahamiyatga ega.*

Kalit so'zlar. *kombinatsiyalashgan piroliz tizimi, issiqxona isitish, biomassa, quyosh energiyasi, pirogaz, biochar, issiqlik utilizatsiyasi, muqobil yoqilg'i, energiya samaradorligi.*

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РАЗРАБОТКА И ОБОСНОВАНИЕ ПАРАМЕТРОВ КОМБИНИРОВАННОЙ СИСТЕМЫ ОТОПЛЕНИЯ ТЕПЛИЦ С ПИРОЛИЗНОЙ УСТАНОВКОЙ

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Аннотация. Введение. *Высокая себестоимость сельскохозяйственной продукции, выращиваемой в современных тепличных комплексах, в значительной степени обусловлена высокой долей энергозатрат. В связи с этим разработка энергоэффективных тепличных систем, основанных на эффективном использовании альтернативных источников энергии, является важной научно-технической задачей.*

Методы и материалы. *В работе для разработки комбинированной системы отопления теплиц с пиролизной установкой использованы экспериментальные методы и термодинамический анализ.*

Результаты. *В результате исследования разработана комбинированная система отопления теплиц с пиролизной установкой и обоснованы её параметры. Предлагаемая система обеспечивает сушку биомассы, получение пирогаза, жидкого топлива и биоугля в процессе пиролиза, а также утилизацию вторичной теплоты дымовых газов.*

Заключение. *Предложенная комбинированная система отопления теплиц с пиролизной установкой позволяет повысить энергетическую эффективность, снизить тепловые потери и обеспечить получение альтернативных видов топлива. Данная система имеет важное значение для обеспечения стабильного теплоснабжения теплиц, использования местных ресурсов и внедрения экологически чистых технологий.*

Ключевые слова: *комбинированная пиролизная система, отопление теплиц, биомасса, солнечная энергия, пирогаз, биоуголь, утилизация теплоты, альтернативное топливо, энергоэффективность.*

Introduction.

The price of fruits and vegetables cultivated in contemporary greenhouse facilities within our country remains quite elevated. This high cost is largely due to the substantial energy consumption, which constitutes roughly 60–70% of the overall production expenses. This is mainly because a considerable amount of thermal energy is needed to sustain ideal microclimatic conditions, particularly during winter when outdoor temperatures plummet significantly. In these circumstances, guaranteeing a consistent and reliable flow of fuel and energy for greenhouse heating systems presents a significant hurdle [1-4].

Furthermore, depending on traditional fossil fuels raises operational expenses and creates environmental issues, such as greenhouse gas emissions and the depletion of resources. The fluctuating nature of fuel prices and constraints on energy supply also worsen the economic viability of greenhouse production [5].

The creation and use of energy-saving greenhouse complexes and protected soil structures, powered by sustainable technologies, is crucial. It is essential to prioritize the use of locally sourced renewable and alternative energy options, including solar power, biomass, and waste heat recovery methods. These methods not only decrease energy usage and operating expenses but also promote environmental responsibility and energy self-sufficiency [6].

Moreover, incorporating cutting-edge technologies, such as combined solar-thermal systems, heat storage mechanisms, and hybrid energy solutions, can dramatically boost the efficiency of greenhouse operations. These systems guarantee a consistent heat supply, optimize resource usage, and establish a stable environment for agricultural activities year-round.

Developing and implementing energy-efficient, environmentally friendly greenhouse complexes tailored to our republic's climate, utilizing local alternative energy sources, is a pressing scientific and technical endeavor. This initiative holds substantial economic and ecological advantages [5].

Materials and methods

The research work used an experimental and theoretical approach to develop and evaluate an autonomous greenhouse heating system with a combined pyrolysis device. The design of the system and the development of a heat-technological scheme were carried out on the basis of heat transfer laws, thermodynamic analysis, and energy balance equations.

As a result of the research, an autonomous heating system for a greenhouse with a combined pyrolysis device was developed. in the developed autonomous heating system with a combined pyrolysis device, firstly, the pyrolysis device allows for the production of alternative fuel from local biomass, and secondly, the device also performs the function of providing additional heat to the greenhouse by using the heat of the flue gases, and allows the heating system to be supplied with hot water at the expense of heat lost to the environment.

The main goal of the research work is to develop a combined pyrolysis heating system for greenhouses that allows for drying biomass, providing alternative fuels (pyrogas, liquid and solid), and utilizing the secondary heat of flue gases.

Results and discussions.

To fulfill its goal, the proposed system comprises a unified collection of functional elements aimed at guaranteeing a constant heat supply, effective biomass drying, and energy recuperation.

This system features a solar air collector equipped with a specialized coating and insulation, all housed within a metal framework. A control valve regulates the flow of heated air from the collector to a distribution duct, ensuring a consistent supply of warm air for the drying process. Within the drying chamber, the biomass is positioned on a metal grid, facilitating even air circulation throughout the material. The chamber features an air intake grille that draws in fresh atmospheric air, along with a direct current (DC) exhaust fan designed to expel the moist air created during the drying procedure.

To maintain a consistent heat source for the drying chamber, a thermal energy storage system utilizing phase change material (paraffin) is positioned in the lower interior. This system incorporates a spiral heat exchange tube that is linked through a water circulation pump to a condenser-cooler assembly. Within the condenser-cooler, a recuperative heat exchanger facilitates the effective capture and recycling of thermal energy.

This system includes a steam-gas pipeline, a gas storage unit, and two liquid fuel tanks, all linked by valves. Liquid fuel is delivered through a nozzle system into a furnace connected to a “pipe-in-pipe” pyrolysis reactor. This reactor is housed within a pipe encased in water, facilitating effective heat transfer and the conversion of fuel.

To guarantee the cleanliness of exhaust gases before they are emitted, the flue gas pipeline utilizes a three-tiered filtration process. This system also incorporates various heat management components for greenhouse heating, including flue gas heat exchangers, water-based heating loops, and underground thermal storage solutions.

Furthermore, the system incorporates an airflow control fan, injectors, and circulation pumps, driven by solar energy harvested through a photovoltaic (PV) array situated on a metal framework. This electrical setup comprises a controller (K), a battery bank (AKB), and inverters (IN), collectively guaranteeing a consistent power supply and independent functionality for the whole system.

This proposed setup combines solar energy and pyrolysis to create a hybrid system. It integrates renewable energy, waste heat capture, and self-sufficient power generation to improve the efficiency and sustainability of greenhouse heating and biomass processing. This integrated approach aims to maximize both energy production and resource management.

The schematic diagram of the combined pyrolysis-based greenhouse heating system developed in this study is presented in Figure 1.

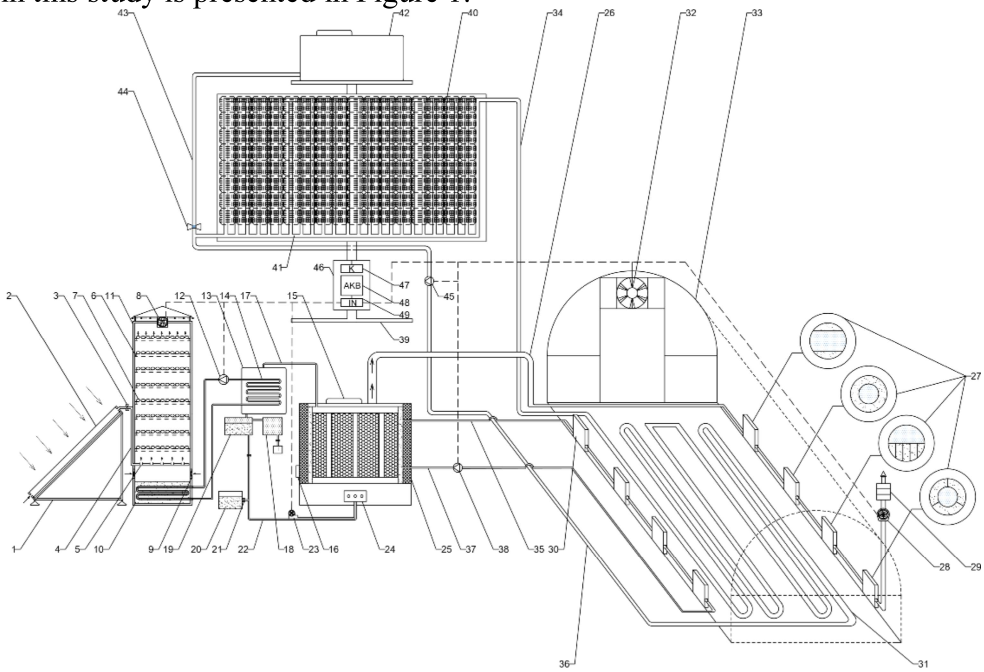

Figure 1. Schematic diagram of a greenhouse heating system with a combined pyrolysis device.

The combined pyrolysis-based greenhouse heating system consists of an integrated set of components designed to ensure continuous heat supply and efficient biomass processing.

The system includes a solar air collector (2) with a selective coating and thermal insulation, mounted on a metal frame (1), which is connected via a valve (3) to a hot air pipeline (4) and a hot air distribution duct (5). Heated air is supplied into a drying chamber (11), where the biomass (7), placed on a metal grid (6), undergoes drying. The chamber is equipped with an atmospheric air inlet grille (9) and a direct current (DC) exhaust fan (8) for removing the humid air mixture generated during the drying process.

In the lower part of the drying chamber (11), a phase change material (PCM)-based thermal storage unit (paraffin) (10) is installed, combined with a spiral heat exchange tube (11). This system is connected via a circulation pump (12) to a condenser-cooler unit (13), inside which a recuperative heat exchanger (14) is installed, ensuring continuous heat supply to the drying process.

The system further includes a biomass loading hatch (15), a charcoal discharge hatch (16), a steam–gas pipeline (17), a gas holder (18), a liquid fuel tank (19), and a reserve fuel tank (20). These components are connected via valves (21) and a liquid fuel pipeline (22) to a blower (23) and a furnace (24), which is integrated with a “pipe-in-pipe” type pyrolysis reactor (25) located within a water-filled pipe system.

The flue gas pipeline (26) is equipped with four types of flue gas–water heat exchangers (27) and is connected to a smoke exhaust fan (28) and a three-stage flue gas filter (29). The greenhouse (33) includes a water heating system (30), a subsurface thermal energy storage unit (31), and an airflow control fan (32).

The system also includes a photovoltaic (PV) power supply unit (40), mounted on a metal support structure (39), which provides electricity to fans (8, 28, 32), circulation pumps (12, 38, 44), and the blower (23). The electrical system is composed of a controller (K) (47), a battery unit (AKB) (48), and inverters (IN) (49), ensuring stable autonomous operation.

Operating Principle. The system operates as follows. During daytime operation, solar-heated air with a temperature of 83–88°C is generated in the solar air collector (2) and transported through the hot air pipeline (4) into the drying chamber (11). The heated air is distributed via duct (5) and supplied to biomass (7) with an initial moisture content of 32–37%, placed on the metal grid (6). Due to convective heat transfer between hot air and biomass, moisture evaporates and is removed by the exhaust fan (8). As a result, the biomass is dried to a moisture content of 17–22%. The dried biomass is then fed through the loading hatch (15) into the pyrolysis reactor (25), where it is heated at temperatures of 300–700°C. The resulting steam–gas mixture is transported via pipeline (17) to the condenser-cooler (13). Through the recuperative heat exchanger (14), heat from circulating water is reused to maintain a stable drying temperature of 82–86°C in the drying chamber. As the steam–gas mixture cools, liquid fuel, pyrolysis gas, and charcoal are produced. The charcoal is removed through hatch (16), while the liquid fuel is stored in tank (19). Up to 30% of the liquid fuel is recirculated to the furnace (24), where it is mixed with air and combusted via a nozzle system. The heat generated from the pyrolysis reactor is transferred to water, producing hot water at 70–80°C, which is supplied to the greenhouse heating system via pipeline (35). Additionally, heat from flue gases at 86–92°C is recovered using flue gas–water heat exchangers (27), where thermal energy is accumulated in water. The cooled flue gases (75–78°C) are passed through a three-stage filtration system (29) and cleaned from harmful components such as CO_2, CO_x, NO_x, and SO_x before release. Simultaneously, the subsurface thermal storage system (31) is supplied with heat via a circulation system connected to the photovoltaic-powered infrastructure.

Figure 2 and Table 1 illustrate a smart greenhouse with a useful area of 50 m^2 and present its thermal and technical parameters.

Table 2.

The thermal and technical parameters of a smart greenhouse with a usable area of 50 m2 are presented.

No	Parameter name and unit of measurement	Value
1	Useful area, m²	50
2	Construction volume, m^3	150
3	Cover type and heat transfer coefficient, W/m^2·°C	Glass / 5.8
4	Heat load, kW	8–10
5	Solar radiation intensity, W/m^2	700–1000
6	Optimal temperature range, °C	16–24
7	Yield (cucumber), kg/m^2	25–30

a) b)

Figure 2. General view of an autonomous greenhouse with a useful area of 50 m² (a) and the cucumber cultivation process (b).

The greenhouse heating system with a combined pyrolysis device developed by the authors is designed to obtain pyrolysis products (pyrolysis liquid, pyrogas and biochar) by thermal processing of any hydrocarbon waste, biomass, rubber, plastic waste, wood and rubber waste, oil-contaminated soil, oil compounds, household waste, industrial waste, medical waste in a pyrolysis reactor, and biomass raw materials in a bioreactor, and to provide the greenhouse with heat load by utilizing the heat of flue gases in the pyrolysis process using various recuperators. The technical characteristics of the greenhouse heat supply system with a combined pyrolysis device are presented in Table 2.

Table 2.

Technical characteristics of the greenhouse heat supply system with a combined pyrolysis device.

No	Construction name	Unit	Value
1.	Working volume of the pyrolysis reactor	m^3	0,5
2.	Processing capacity of the pyrolysis reactor	kg/day	550÷650
3.	Number of pyrolysis reactors	pcs	1
4.	Rated voltage	V	220
5.	Rated frequency	Hz	50
6.	Total height of the pyrolysis reactor	m	2
7.	Inner diameter of the pyrolysis reactor	mm	500
8.	Outer diameter of the pyrolysis reactor	mm	505
9.	Number of condensers	pcs	1
10.	Liquid fuel tank	pcs	1
11.	Gas storage tank	pcs	1
12.	Number of filters	pcs	1

Conclusion

The greenhouse heat supply system, incorporating a combined pyrolysis device, demonstrates significant potential for improved efficiency. By minimizing heat losses through the effective use of secondary heat energy produced within the device (ranging from 60% to 85%), this system can achieve an 85-90% increase in overall useful work coefficient and a 65-75% enhancement in exergy efficiency. This improvement stems directly from the thermal and technical characteristics of the design.

By using the combined pyrolysis heating system of a greenhouse in an autonomous heating system of a greenhouse with a useful area of half a square meter, it was possible, firstly, to obtain alternative fuels based on thermochemical processing of biomass and various hydrocarbon waste, as well as to additionally provide the greenhouse with full thermal energy. As a result of the integration of pyrolysis processes, it was determined that 18 thousand m3 of pyrogas, 15 tons of biochar, and 24 tons of pyrolysis liquid can be obtained per year.

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