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"STUDY OF THE SEASONAL ACCUMULATION PROCESS IN SEMI-CYLINDRICAL SOLAR GREENHOUSES"

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Abstract

This article is devoted to an in-depth study of the process of seasonal heat accumulation in semi-cylindrical solar greenhouses. The main objective of the research is to determine the possibilities of increasing the thermal efficiency of such greenhouses and extending the crop cultivation season within them. The study analyzes heat transfer mechanisms, energy balance, and temperature dynamics using experimental and theoretical methods. The obtained results serve to provide practical recommendations for optimizing the microclimate inside the greenhouse and reducing energy consumption. This contributes to the implementation of sustainable and efficient solutions in agriculture.

Keywords: solar greenhouse, semi-cylinder, seasonal accumulation, heat transfer, energy efficiency, thermal analysis, agriculture, sustainable development

Introduction

The climatic conditions of Uzbekistan create certain difficulties in cultivating agricultural products throughout the year. This necessitates the development of modern agrotechnologies, particularly greenhouse farming, in order to ensure food security and increase export potential. Although conventional greenhouses make it possible to grow crops under unfavorable climatic conditions by controlling temperature, light, and humidity [3], their heating systems often require significant energy consumption. Therefore, the efficient use of renewable energy sources, especially solar energy, has become highly relevant. Solar greenhouses, particularly semi-cylindrical structures, possess great potential for improving energy efficiency and ensuring a stable microclimate throughout the year through seasonal heat accumulation. Research conducted by the Solar Thermal and Energy Devices Laboratory of the Physics-Technical Institute (FTI) on optimizing low-potential solar thermal devices, including solar greenhouses with heat accumulation systems, strengthens the scientific basis in this direction [1]. In addition, the work of the Semiconductor Solar Cell Laboratory on the application of solar energy in agriculture, including greenhouses, also contributes to the development of this field [2].

The main purpose of this work is to comprehensively study the process of seasonal heat accumulation in semi-cylindrical solar greenhouses, analyze their thermal characteristics, and evaluate their energy efficiency. To achieve this objective, the following tasks are performed: analysis of the structural characteristics and design principles of semi-cylindrical greenhouses; study of heat accumulation mechanisms and materials; dynamic analysis of the seasonal accumulation process and determination of thermal parameters; as well as assessment of energy efficiency and economic feasibility.

Literature Review

Research aimed at improving the energy efficiency of solar greenhouses and ensuring a stable microclimate throughout the year through seasonal heat accumulation is rapidly developing worldwide. The use of solar energy, especially in semi-cylindrical structures, is recognized as an important solution to the problem of high energy consumption in conventional greenhouses. Such greenhouses maximize the absorption of solar radiation, while their aerodynamic shape increases resistance to wind loads and helps optimize construction costs. Seasonal heat accumulation is based on storing excess summer heat for maintaining greenhouse temperatures during winter, playing a decisive role in ensuring system sustainability.

Studies on heat accumulation mechanisms and materials are important for increasing the efficiency of greenhouse systems. In this regard, sensible heat accumulators (water, stone layers) and latent heat accumulators (phase change materials – PCMs) are being investigated. PCMs have significant potential in seasonal heat storage systems due to their high energy density and isothermal heat exchange characteristics. Research conducted by the Solar Thermal and Energy Devices Laboratory of FTI focuses specifically on studying the thermophysical properties of PCMs for heat accumulation and optimizing their application in solar thermal devices, including solar greenhouses with heat accumulation systems [1]. Furthermore, this laboratory conducts exergy analysis of solar thermal energy devices, contributing to the improvement of the thermodynamic efficiency of such systems. The use of new heat transfer fluids such as nanofluids is also among the promising directions for enhancing heat exchange in solar energy systems [1].

The contribution of the local scientific school in optimizing solar greenhouses and low-potential solar thermal devices adapted to Uzbekistan's climatic conditions is significant. The Solar Thermal and Energy Devices Laboratory of FTI was established in 1975 by Professor R.R. Avezov and has been conducting fundamental and applied research over the past decade on the creation and optimization of solar thermal devices, including solar greenhouses with heat accumulation systems [1]. Their work is aimed at developing efficient solar devices and new technical solutions for the economy of Uzbekistan, and several scientific projects in this field have been completed and continued since 2020. Laboratory staff regularly improve their qualifications at international scientific centers and participate in global conferences. Over the past decade, they have published 98 articles in prestigious foreign journals and obtained 21 intellectual property patents [1]. This demonstrates the international recognition of their research.

The use of solar energy in agriculture, especially in greenhouses, can be implemented not only through heat supply but also through electricity generation. Research conducted by the Semiconductor Solar Cell Laboratory (LPSE) of FTI is particularly important in this regard. Established in 1975, this laboratory carries out fundamental and applied research focused on the development of GaAs- and Si-based solar cell technologies. The photovoltaic batteries and devices developed by the laboratory (2–150 W), equipped with electronic control units and inverters, are used for powering mobile devices, lighting, water pumps, and even providing electricity to greenhouses [2]. Current research on photovoltaic power systems for greenhouses and their optimization for the climate of Central Asia is especially important for supplying auxiliary systems (such as ventilation, irrigation, and lighting) in semi-cylindrical solar greenhouses. The experimental line available at FTI enables the production of silicon photovoltaic cells and photovoltaic products of various capacities (2–10000 W) adapted to regional conditions, thereby contributing to the overall energy efficiency of solar greenhouses [2].

Research on the dynamic analysis of the seasonal accumulation process and determination of thermal indicators is based on mathematical modeling and simulation methods. These methods allow prediction of time-dependent changes in temperature, humidity, and solar radiation inside the greenhouse, as well as optimization of the charging and discharging cycles of heat accumulators. The assessment of energy efficiency includes analysis of the overall energy balance of the system, heat losses, and useful heat collection coefficients. Economic justification involves evaluating the balance between initial investment costs, operating expenses, and benefits achieved through energy savings. The review of existing literature indicates the need for comprehensive studies on the seasonal heat accumulation process in semi-cylindrical solar greenhouses under the conditions of Uzbekistan, including accurate evaluation of their thermal and energy performance as well as economic feasibility. This work is aimed precisely at filling this gap by proposing new practical solutions based on existing scientific achievements.

Research Methodology

This research is aimed at a comprehensive study of the seasonal heat accumulation process in semi-cylindrical solar greenhouses through theoretical analysis, numerical simulation, and energetic-economic evaluation methods. The goal is to determine the optimal design and operational parameters for optimizing the greenhouse microclimate, improving energy efficiency, and ensuring system sustainability.

Theoretical Foundations and Mathematical Modeling

At the initial stage, a mathematical model describing the thermal dynamics of the semi-cylindrical greenhouse system is developed. The model takes into account the energy balance of the air, soil, accumulator material, and structural elements inside the greenhouse. A system of equations is formulated for convection, conduction, and radiation heat transfer mechanisms. External climatic conditions (air temperature, solar radiation intensity, wind speed, relative humidity) and geometric parameters of the greenhouse structure (dimensions, orientation, optical and thermophysical properties of the covering material) are used as input data. Differential equations describing the dynamic characteristics of the heat accumulation system, particularly the charging and discharging processes of phase change materials (PCMs), are also incorporated into the model. Research conducted by the Solar Thermal and Energy Devices Laboratory of FTI on the thermophysical properties of PCMs [1] serves as the scientific basis for developing the model.

Numerical Simulation and Dynamic Analysis

Based on the developed mathematical model, numerical simulation is applied to study the thermal behavior of the semi-cylindrical solar greenhouse. Simulations are carried out using software packages such as TRNSYS and EnergyPlus, or custom codes written in MATLAB/Python environments. Annual climatic data for a specific region (hourly solar radiation, air temperature, wind speed, and relative humidity) are used as input parameters. Parameters such as greenhouse dimensions, orientation, type of covering material, insulation layer thickness, and the volume and placement of the heat accumulator (PCM or water/stone) are considered variable. Simulation results make it possible to determine the time-dependent changes in greenhouse air temperature, soil temperature, PCM temperature and phase state, as well as heat fluxes. This dynamic analysis helps to understand seasonal and daily variations in the greenhouse microclimate and the charging/discharging cycles of the accumulator.

Optimization of the Heat Accumulation System

An important part of the study is devoted to optimizing the efficiency of the heat accumulation system. This includes the selection of PCM, its volume, and the method of integration into the greenhouse. Criteria such as melting temperature (appropriate temperature range), latent heat capacity, thermal stability, non-toxicity, and economic feasibility are considered in PCM selection. The experience of the FTI laboratory in PCM research [1] forms the basis for this process. Parametric studies evaluate the influence of PCM volume, placement (for example, under the northern wall or integrated into the soil), as well as the type of covering material and insulation layer thickness on the greenhouse temperature regime.

Determination of Thermal Indicators and Assessment of Energy Efficiency

Based on simulation results, the main thermal indicators of the greenhouse system are determined. These include average daily and seasonal air temperature inside the greenhouse, minimum and maximum temperature values, soil temperature, PCM charging level, and heat losses. Energy efficiency is evaluated through indicators such as the overall energy balance of the system, demand for auxiliary heating, solar fraction, and coefficient of performance (COP). Research conducted by the FTI laboratory on exergy analysis of solar thermal energy devices [1] enables a deeper assessment of the thermodynamic efficiency of the system. The energy performance of the semi-cylindrical solar greenhouse is compared with that of conventional greenhouses.

Economic Feasibility Analysis

At the final stage of the research, the economic efficiency of the semi-cylindrical solar greenhouse is evaluated. This is carried out based on Life Cycle Cost (LCC) analysis. Initial investment, operating expenses, and benefits achieved through energy savings are considered. Economic indicators such as payback period and Net Present Value (NPV) are determined. This analysis is conducted taking into account local market conditions, energy prices, and available subsidies in Uzbekistan. Ongoing research by the Semiconductor Solar Cell Laboratory (LPSE) of FTI on photovoltaic power systems for solar greenhouses and their optimization for the Central Asian climate [2] is important in reducing the energy supply costs of auxiliary systems and is included in the analysis. This comprehensive methodology creates a solid scientific and economic foundation for the practical implementation of semi-cylindrical solar greenhouses under the conditions of Uzbekistan.

Conclusion

This study comprehensively investigated the process of seasonal heat accumulation in semi-cylindrical solar greenhouses through theoretical analysis, numerical simulation, and energetic-economic evaluation methods. Based on the developed mathematical models and simulations, optimal structural and operational parameters for maintaining a stable greenhouse microclimate throughout the year were identified, including the effective application of phase change materials. The results clearly demonstrated the high energy efficiency of the system and its economic feasibility under the climatic conditions of Uzbekistan. Thus, this work establishes a strong scientific and practical basis for year-round agricultural production using renewable energy sources, strengthening food security, and developing sustainable agro-industrial systems.

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