BAIMBETOV DINMUKHAMBET BAIMBETOVICH

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF HEAT PUMP ASSISTED REGENRATIVE SOLAR STILL

ANNOTATION

Dissertation for the degree
Doctor of Philosophy (PhD) in specialty
«6D060300 – Mechanics»

General description of the work. The dissertation is dedicated to the experimental and numerical study of a solar still with a heat pump. The research focuses on investigating the connection scheme of the heat pump to the solar still and intensifying the condensation process to increase the production of clean water.

Relevance of the work. According to UN data on the state of the world's water resources, 2 billion people worldwide (26% of the population) do not have access to safe drinking water, and 3.6 billion people (46%) lack access to safe sanitation. The issue of drinking water scarcity has not bypassed the regions of Kazakhstan. The southern, central, and western regions experience shortages of drinking water, with the southwestern region (Mangystau region) being the only one with access to the Caspian Sea, where seawater desalination methods can be applied. In this region, there are two main sources of drinking water, where thermal desalination and reverse osmosis methods are used.

There is a need in this region for the development of autonomous, mobile installations utilizing renewable energy sources for remote settlements and rural areas that do not have access to centralized utilities (electricity, water supply, etc.). Mangystau region also has significant potential for solar energy. Due to the region's climatic conditions, the efficiency of heat pumps is very high. This work will focus on the development of an experimental solar-thermal desalination system based on a heat pump in the conditions of Mangystau region, Kazakhstan..

Objective of the work. The objective is to investigate the intensification of water vapor condensation inside a solar still by integrating a vapor-compression heat pump.

Tasks of the work.

- Assembly of a prototype of a single-slope solar still and heat pump, with subsequent integration;
- Assembly of measuring instruments, including a weather station and data collection system;

- Development of a mathematical model of the thermal balance of the components of the solar still with the heat pump, considering various system configurations, and creation of a computer program for calculations in Python;
- Processing of experimental data and validation of the numerical model by comparing it with the obtained results;
- Analysis of clean water productivity in the climatic conditions of Aktau.
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Research methods. The research methods include the assembly of a prototype of a single-slope solar still and heat pump, their integration for joint operation, and the installation of measuring instruments, including a weather station and data collection system. A mathematical model of the thermal balance of the system was developed and implemented as a Python program for numerical calculations. Experimental data obtained using the monitoring system were processed and compared with the results of numerical modeling for model validation. The performance of the system was analyzed based on the amount of desalinated water in the climatic conditions of Aktau.

Scientific novelty.

- Integration of the heat pump evaporator into the solar still to heat the water in the tank;
- Integration of the evaporator and condenser of the heat pump into the solar still for heat regeneration.

Scientific findings submitted for defense.

- Experimental and numerical results of the analysis of water vapor condensation intensification by integrating only the heat pump evaporator into the solar still;
- Numerical results of the analysis of water vapor condensation intensification by integrating both the evaporator and condenser of the heat pump into the solar still.

Description of the main research results. During the research, a prototype of a single-slope solar distiller with an integrated heat pump was designed, developed, and tested, providing an opportunity to evaluate its efficiency under real-world conditions. The experimental data obtained confirmed that the use of a heat pump significantly increases the distiller's performance by enhancing the condensation processes and improving heat exchange. This is particularly crucial in scenarios requiring high output with minimal energy consumption.

Additionally, a mathematical model of the system's heat balance was developed and successfully validated based on experimental data. This model accurately predicts the behavior of the solar distiller with a heat pump in various climatic conditions, including extreme weather situations such as high temperatures and intense solar radiation, which are typical for the Mangystau region. The model also takes into account key parameters such as solar radiation intensity, air humidity, and temperature fluctuations, making it a versatile tool for analyzing system performance in other regions.

The system's performance was thoroughly analyzed under the climatic conditions of Aktau city, characterized by harsh weather, arid conditions, and high solar activity. The results demonstrated that this system not only operates effectively in such environments but also presents a promising solution for providing fresh water to remote settlements in the Mangystau region. This is particularly relevant for areas with limited access to centralized infrastructure, where autonomous and mobile systems may be the only viable source of water. Therefore, the proposed system has significant potential for use in arid regions facing freshwater scarcity.

Scientific novelty of the obtained results. The scientific novelty lies in the development of an integrated solar distillation system with a heat pump, which enhances performance by intensifying the condensation processes. For the first time, a mathematical model of heat balance has been proposed, which takes into account the impact of the heat pump on the desalination processes. This model has been successfully validated based on experimental data, making it applicable for further research and development of similar systems. Within the framework of the study, two configurations of connecting the heat pump to the solar distiller were considered. In the first configuration, the evaporator of the heat pump was located inside the solar distiller, and both experimental and numerical studies were conducted. In the second configuration, where both the evaporator and condenser of the heat pump were placed inside the solar distiller, only numerical studies were performed.

Practical significance of the work. The practical significance of this research lies in its potential to address water supply challenges in remote and arid regions. The integrated solar distillation system with a heat pump is designed for autonomous freshwater production, making it particularly relevant for areas with limited resources and far from centralized water supply systems. The system can operate without external energy sources, significantly reducing operational costs and making it an economically viable solution for such regions.

The developed prototype demonstrates high desalination efficiency, and its design can be scaled to create larger installations capable of supplying not only small settlements but entire regions with water. Moreover, the mathematical model proposed within this work can be used for the optimization and design of future desalination systems, enabling engineers to develop systems with improved performance and lower operating costs.

This research also provides a foundation for modernizing existing desalination systems. The integration of a heat pump can significantly increase the productivity and reduce the energy consumption of current desalination technologies. Thus, the results of this work can contribute to the development of sustainable water supply technologies, playing a crucial role in supporting the sustainable development of regions facing freshwater scarcity.

Connection of the work with state scientific programs.

This work was carried out within the following projects:

- "Modeling and development of a solar heat pump system for seawater desalination in the southwest region of Kazakhstan" (2023-2025, AP19175769);

- "Development of a solar thermal desalination system based on a heat pump" (2022-2024, AP14871988).

Individual Contribution of the Doctoral Candidate to the Preparation of Articles

The doctoral candidate independently formulated the scientific problem and research objectives, developed an experimental setup for the first configuration of the solar distiller with a heat pump, and conducted the necessary experiments. Additionally, the doctoral student developed a mathematical model of the system's heat balance and performed numerical studies for both configurations. The doctoral student analyzed the results, compared the experimental data with the numerical model, conducted a literature review, prepared graphs and diagrams, and handled the formatting and submission of articles to scientific journals.

The doctoral candidate made a significant contribution to the preparation of two scientific articles published in international journals indexed in Scopus and/or Web of Science.

1. D. Baimbetov, Ye.Karlina, Ye.Yerdesh, S.Syrlybekkyzy, A.Toleukhanov, M.Mohanraj, Ye.Belyayev. Thermal analysis of a compression heat pump-assisted solar still for Caspian regions of Kazakhstan // Springer Nature, Journal of Thermal Analysis and Calorimetry (2024). https://doi.org/10.1007/s10973-024-13446-4 (WoS: Квартиль – Q2, Scopus: Процентиль – 87, SJR – 0.585). The author of the dissertation participated in setting the tasks, developing the program code, performing calculations and preparing the articles. He was the first author.

2. Baimbetov, D.; Yerdesh, Y.; Karlina, Y.; Syrlybekkyzy, S.; Radu, T.; Mohanraj, M.; Belyayev, Y. / Numerical Estimation of Potable Water Production for Single-Slope Solar Stills in the Caspian Region // MDPI. Water 2024, 16, 2980. doi.org/10.3390/w16202980. (WoS: Квартиль – Q2, Scopus: Процентиль – 84, SJR – 0.724)

3. S.Syrlybekkyzy, A.Zhidebayeva, A.Aitimova, D. Baimbetov, L.Taizhanova DEVELOPMENT AND EVALUATION OF THE EFFECTIVENESS OF NEW DESIGNS OF SOLAR DESALINATION POOLS FOR THE PRODUCTION OF FRESH WATER IN HOT CLIMATES // National Academy of Science Republic of Kazakhstan, News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences (стр. 179-195, №4, 2024). https://doi.org/10.32014/2024.2518-170X.418 (WoS: Квартиль – Q3, Scopus: Процентиль – 42, SJR – 0.378). The author of the dissertation participated in setting the tasks, developing the program code, performing calculations and preparing the articles.

1 article in scientific publications recommended by the Committee for Quality Assurance in Science and Higher Education (KOKSNVO) of the Republic of Kazakhstan for publishing the main results of scientific activity:

1. Е.И. Карлина, Е.Б. Ердеш, Д.Б. Баимбетов, И.Б. Джамакеев, М. Моханрадж, Е.К. Беляев. *«ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ДВУХФАЗНОГО ТЕПЛООБМЕНА ПРИ ИСПАРЕНИИ И КОНДЕНСАЦИИ ВНУТРИ СОЛНЕЧНОГО ДИСТИЛЛЯТОРА» была опубликована в журнале «Вестник Казахстанского-Британского технического Университета» входящий в перечень изданий,*

рекомендуемых КОКНВО МНВО РК(https://doi.org/10.55452/1998-6688-2024-21-3-281-301). The author of the dissertation participated in setting the tasks, developing the program code, performing calculations and preparing the articles.

2 abstracts at international scientific conferences:

1. D. Baimbetov. Experimental and Numerical Study of Solar Still for the Caspian Region of Kazakhstan // The 19 th Conference on Sustainable Development of Energy, Water and Environment Systems(*SDEWES-2024*) (University of Sapienza, Rome, Italy), He gave a report.
2. D. Baimbetov. Thermal performance analysis of a heat pump assisted regenerative solar still // 3rd Journal of thermal analysis and Calorimetry Conference and 9th V4 (Joint Czech-Hungarian-Polish-Slovakian) Thermoanalytical Conference 2023 / June 20–23, 2023 / Balatonfüred, Hungary