Heat pump system for the utilization of renewable energy sources

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Abstract. The use of renewable energy sources (RES) in agricultural processes, the reduction of conventional energy consumption, and energy conservation are important technological and economic challenges. The proposed heat pump system enables the utilization of solar energy, as well as recovered heat from animals, milk, and the ground. The system is integrated with and closely interacts with technological processes, regulating thermal conditions of the microclimate, product cooling, and storage, while simultaneously recovering excess heat generated during these processes. The article describes the system's design, operating principle, and key performance characteristics. An assessment was carried out to evaluate the functional performance of the system when operating as part of a cowshed microclimate system; its compliance with technical specifications; and the quality and stability of technological process performance over a specified period.

1 Introduction

The development of global civilization, intensification of economic growth, increasing energy consumption, and the associated environmental pollution have reached a critical threshold [1-3]. This issue is highly acute and global in nature. Measures to address it are being undertaken through the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) [4].

It has been determined that the main sources of pollution are emissions from the combustion of conventional energy carriers, including coal, petroleum products, and natural gas. The primary criteria for assessing environmental conditions include accounting for and regulating atmospheric emissions of combustion products, improving the efficiency of energy-saving measures, and reducing the environmental impact of industrial enterprises. Significant investments are planned for new technologies aimed at reducing CO_2 emissions, including the development and use of renewable energy sources (RES) [4-6].

One of the emerging directions in renewable energy is a multi-zone system (MZS) for the utilization of RES, based on the integration (summation) of secondary heat generated during technological processes and renewable energy sources. The system also provides product

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cooling, air conditioning, and the beneficial use of excess thermal energy. As a result, a significant energy-saving and environmental effect is achieved.

The proposed system has been developed specifically for application in livestock farms. Therefore, it differs from existing solutions in terms of design, functions performed, and operating parameters [7, 8].

2 Materials and methods

A literature review and patent analysis, conducted using databases of domestic and international scientific journals as well as patent fund materials, made it possible to identify the current state and key development trends of heat pump systems utilizing renewable energy sources (RES). It was established that existing solutions are generally focused on a single type of RES (e.g., geothermal, air, or solar energy) and are limited in functionality. Based on this analysis, promising design and technological solutions were substantiated, aimed at improving the efficiency, versatility, and adaptability of the system.

Theoretical studies were carried out using thermodynamic methods, including analysis of energy balances, heat transfer processes, and phase transitions in the heat pump working fluid. The calculations confirmed the feasibility of stable system operation when combining multiple energy sources and demonstrated an increase in the overall coefficient of performance (COP) through optimization of operating modes and redistribution of heat flows.

The key novelty of the developed system lies in the implementation of a set of technical solutions that ensure multifunctionality and a high level of energy integration. In particular, the proposed devices and design solutions enable:

• the summation of energy flows from several renewable sources of different physical nature (solar radiation, thermal energy of soil, air, and water). This is achieved through the use of combined heat exchangers and an intelligent control system that selects the optimal source or their combination depending on current conditions;

• efficient cooling of products, which is especially important for industrial and agro-industrial facilities. The system can operate in a refrigeration mode, removing excess heat and maintaining required storage temperature conditions;

• air conditioning in rooms with simultaneous use of the extracted heat for domestic hot water supply or heating. Thus, the principle of energy recovery is implemented, significantly reducing overall energy consumption;

• utilization of excess secondary thermal energy generated during technological processes. Unlike traditional systems, where such energy is lost, the proposed system accumulates and reuses it, increasing overall energy efficiency.

An additional feature is the modular design principle, allowing adaptation to various operating conditions and application scales. This ensures design flexibility and the possibility of integration into existing engineering networks.

Thus, the developed heat pump system represents an innovative solution combining the functions of energy generation, cooling, air conditioning, and heat recovery. Its implementation makes it possible to significantly increase energy efficiency, reduce operating costs, and minimize environmental impact through more efficient use of renewable energy sources [8].

3 State of the problem and research

In the proposed system (Figures 1 and 2), low-potential heat sources (LPHS) to be converted and utilized include: ground heat (GH), milk heat (MH), secondary technological heat (STH), and solar energy heat (SEH). For this purpose, a system has been developed consisting of: a heat pump (HP) 1, a ground heat exchanger 2, a milk cooler (MC) 3, a microclimate unit 4, a solar collector (SC) 5, and a thermal energy storage unit (TES) 6.

Functionally, the system is divided into four subsystems: "HP–solar collector," "HP–microclimate," "HP–milk cooler," and "HP–ground heat exchanger."

The system operates as follows: At start-up, a microprocessor control unit selects and connects one of the four heat sources to the heat pump, taking into account task priority. In other words, one of the subsystems operates at a time, and heat from the selected source is supplied to the evaporator of the heat pump via a circulation pump 9. The heat is then absorbed by the refrigerant circulating within the internal circuit of the heat pump. The refrigerant, compressed by the compressor, transfers heat to the condenser. From the condenser, heat is removed by the heat transfer fluid and stored in the thermal energy storage unit.

For example, during night-time, when animals are in the cowshed, the system extracts excess heat from the indoor air through the heat exchanger of the microclimate unit. At the same time, along with heat recovery, air conditioning is performed, maintaining indoor air parameters at the required level.

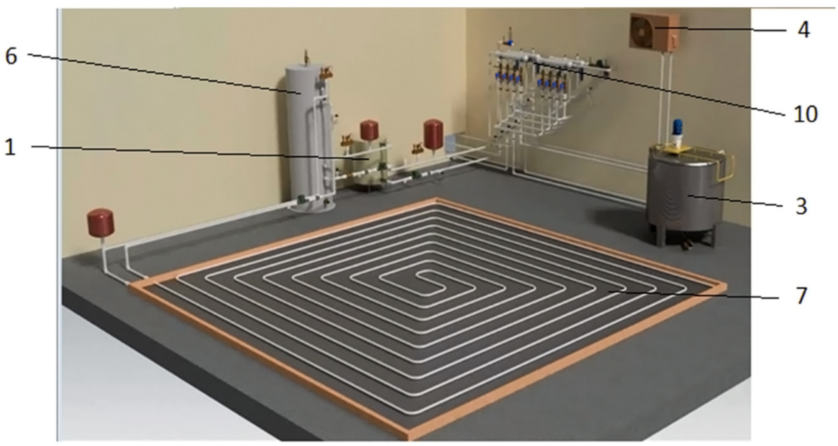

Fig. 1. General view of the laboratory test bench.

In the morning, after milking, the heat pump (HP) is automatically connected to the milk cooler and extracts heat from it. At the same time, the milk is cooled to the required standard temperature within a specified period.

During daytime, switching valves connect the solar collectors (5) to the evaporator of the heat pump. In the absence of solar radiation, the heat pump is connected to the ground heat exchanger (2) and extracts heat from the surrounding soil layer until a specified ground temperature is reached.

The heat accumulated in the thermal energy storage unit (TES) can be supplied, using a circulation pump, either to the underfloor heating system (7) or to the domestic hot water supply. If necessary, an electric heater (heating element) installed in the lower part of the TES is used to raise the hot water temperature to the required technological level. Cold water is supplied from the water supply system through a pipeline.

The schematic diagram and general view of the laboratory test bench for studying the characteristics of the "HP–solar collector" subsystems are shown in Figure 2.

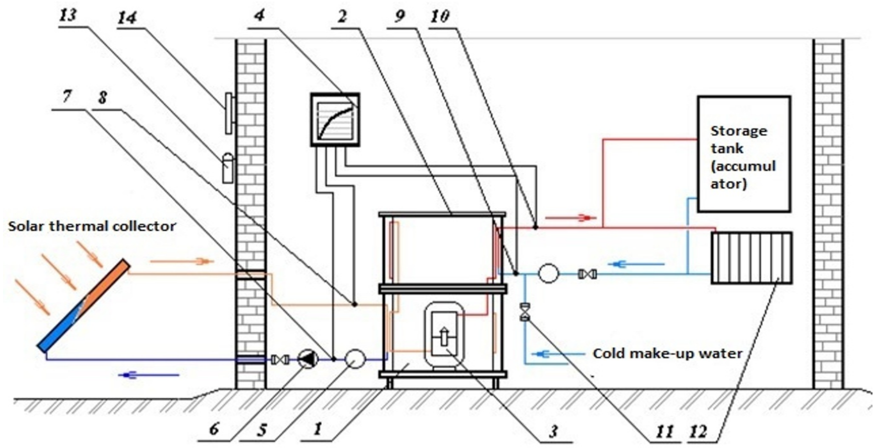

Fig. 2. Schematic diagram of the studied "HP–solar collector" subsystem -1, 2, and 3 respectively: evaporator, condenser, and compressor of the heat pump; 4 – measuring unit; 5 – flow meter; 6 – circulation pump; 7, 8, 9, 10 – temperature sensors; 11 – valve; 12 – heating load; 13 – pyranometer; 14 – thermometer.

The studies are carried out during both winter and summer periods. During the experiments, the following parameters are recorded: t_1, t_2, t_3, t_4, G_1, G_2. The measurement frequency is selected depending on the process dynamics. At the same time, readings of the pyranometer (E) and ambient temperature (t_m) are recorded.

During the simulation of the system's operation under a heating load, the temperature at the inlet (t_2) and outlet (t_1) of the HP condenser is measured. The same RNPIE stages as in the first series of experiments are simulated. Temperature graphs are plotted, and approximating functions are determined. The output power of the heat pump (P_1) is calculated for RNPIE stages ranging from 500 to 4000 W.

The characteristics of solar collectors with and without a transparent cover are investigated. The power generated by the solar collectors is calculated using the following formula:

$$P_1 = c_p \cdot G_1 \cdot (t_2 - t_1) \cdot \frac{1}{S} \quad (1)$$

where: t_1 and t_2 are the temperatures of the heat transfer fluid at the inlet and outlet of the solar collector, respectively, °C; S is the area of the solar collector, m².

The heat pump system (HPS) test bench includes a heat pump (HP), which consists of an evaporator, a condenser (2), and a compressor (3). The heat pump is the central energy unit of the test bench. The compressor drive power is Pcomp=0.7 kWP.

A conventional low-potential energy source (LPES) is represented by its model – an electric water heater (EWH), connected via a direct (red line) and return (blue line) pipeline to the HP evaporator. It serves as a heat energy source for the heat pump. Voltage is supplied to the EWH through a variable autotransformer (ATR). By setting the required output voltage of the ATR, the corresponding power of the LPES model is adjusted.

Experiments are carried out at LPES power levels: PLPES=500, 1000, 1500, 2000, 3000, 4000W.

A heating radiator (12) and a thermal energy storage tank, connected to the HP condenser, serve as the thermal load for the HP system. Circulation pumps (6) provide fluid flow in the evaporator and condenser circuits of the heat pump. Valve (11) is used for supplying feed water into the heating system circuit.

Temperature measurements of the heat transfer fluid are performed using a multi-channel data logger (4) based on signals from chromel–copel thermocouples (CC), installed at the inlet (7) and outlet (8) of the EWH, as well as at the inlet (9) and outlet (10) of the HP condenser. Flow meters (5) are used to measure the time-dependent flow rates of the heat transfer fluids circulating in the evaporator and condenser circuits of the heat pump.

The electrical energy consumption of the HP compressor is measured using a set of electrical measuring instruments K505, which in the schematic diagram is installed between the ATR and the EWH.

Experiments with solar collectors with and without a transparent cover are carried out under identical conditions. For this purpose, a period of stable solar radiation from 12:00 to 15:00 was selected.

The results of the experimental measurements are shown in Figure 3. In the graphs, the left vertical axis represents the variation of temperature over time, while the right vertical axis represents the variation of heat output. The experiments were conducted under winter conditions in both cloudy and sunny weather.

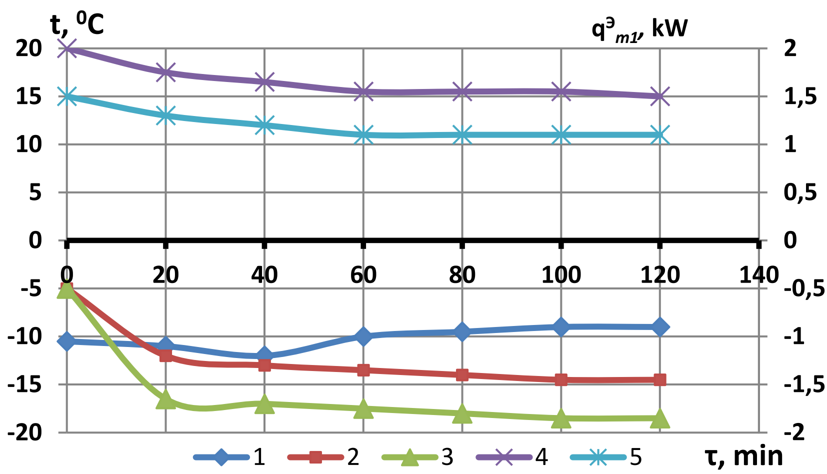

Fig. 3. Temperature and energy characteristics of the "HP–solar collector" subsystem under winter conditions and cloudy weather: 1 – t_t – ambient temperature; 2, 3 – t_1, t_2 – heat transfer fluid temperatures at the inlet and outlet of the solar collector; 4 – $q_{et}1$ – heat output of the heat pump (HP); 5 – $P_{(гк)}$ – heat output of the solar collector.

Analysis shows that: at an ambient temperature of −10 °C and under dense cloud cover, the antifreeze solution supplied from the heat pump to the solar collector had a temperature of −18 °C. While flowing through the solar collector, its temperature increased by approximately 4 °C. In this case, the calculated heat output of the solar collector ranged from 1.1 to 1.5 kWh, while the heat output of the heat pump (HP) was $q_{et}1$ = 1.5…2.0 kWh. The average calculated coefficient of performance was φ = 1.9…2.5.

In sunny conditions, the average intensity of total solar radiation was E_t = 0.1…0.3 kW/m². From the obtained graphs, it can be seen that at an ambient temperature of −8…−10 °C, the antifreeze supplied from the heat pump to the solar collector had a temperature in the range of −5 to −10 °C, with a heat transfer fluid flow rate of 350–400 L/h. While passing through the solar collector, it was heated by an average of 5–8 °C.

The calculated heat output of the solar collector was $P_{(gk)}$ = 2.0…2.2 kWh, while the heat output of the heat pump (HP) was $q_{et}1$ = 2.5…2.7 kWh. The average calculated coefficient of performance was φ = 3.0…3.5.

The results of calculations of the daily average heat output of the "HP–solar collector" subsystem for the conditions of the Almaty region are presented in Figure 4.

Six heating months (October to March) were taken as the calculation period, assuming an average daily operation of 8 hours. The lower graph (curve 1) shows the energy consumption for driving the heat pump compressor. The upper curves show the heat output at different solar collector areas (Ssc = 1, 2, 4, and 10 m²).

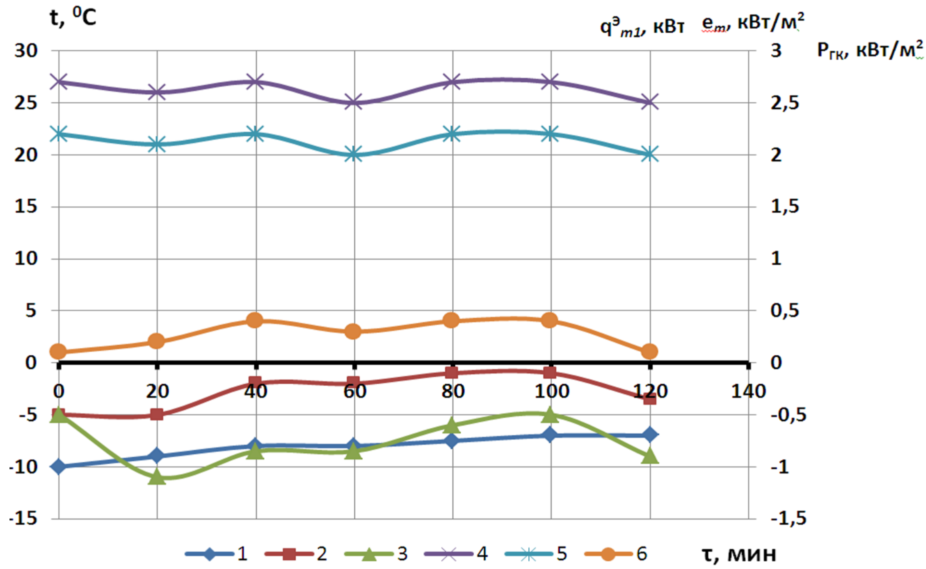

Fig. 4. Temperature and energy characteristics of the "HP–solar collector" subsystem under winter conditions in sunny weather: 1 – t_t – ambient temperature; 2, 3 – t_1, t_2 – heat transfer fluid temperatures at the inlet and outlet of the solar collector; 4 – $q_{et}1$ – heat output of the installation; 5 – $P_{(ГК)}$ – specific power generated by the solar collector; 6 – E_t – solar radiation intensity.

4 Discussion

During the heating period, the system is efficient, as the useful generated energy exceeds the energy consumed to drive the heat pump compressor. The observed patterns have a parabolic character, where the minimum heat output occurs in December–January. In October and March, the heat output is at its highest due to increased ambient air temperature and higher solar radiation intensity. An increase in the heat transfer fluid temperature in the solar collector leads to an increase in the heat transfer coefficient (ktr) of the heat pump.

In conventional systems, heat and cooling supply are provided by consuming traditional energy carriers (electricity, gas, liquid fuels, or coal), as well as solar energy and electrical energy for driving the compressor of the refrigeration machine. When a multi-zone system (MZS) is applied, the structure of energy carriers changes (Table 1).

The exergy sources in the new system include heat from the surrounding atmospheric air, which is additionally utilized alongside solar energy.

The "HP–microclimate" subsystem not only regulates the thermal regime but also recovers heat accumulated in the building from animals and from the ventilated air.

The "HP–milk cooling" subsystem cools milk while simultaneously recovering the heat removed from the cooled milk.

These types of energy can be classified as exergy, since in conventional systems they were potentially present but not utilized. The proposed system enables their effective recovery and utilization. As established, their energy potential is significant.

The “HP–solar collector” subsystem provides heat output even at sub-zero ambient temperatures. The heat output structure consists of three components: absorbed direct solar radiation, heat from atmospheric air, and heat generated by compressor operation.

Table 1. Energy Carrier Structure in Conventional and New Systems

Processes	**Energy sources**		**Exergy sources generated in the MZS application**
	Conventional baseline system	**MZS**	
Domestic hot water supply, Space heating	Conventional energy sources, solar energy	Conventional energy sources, solar energy, ambient air heat	Ambient air heat
Microclimate control	Conventional energy sources, solar energy	Conventional energy sources, solar energy, animal heat	Animal heat, ambient air heat
Perishable product cooling	Electrical energy (for driving the refrigeration compressor)	Electrical energy (for driving the heat pump compressor)	**Milk heat**

The ratio of these energy contributions depends on the solar collector area and ambient temperature variation. The main share is contributed by solar energy and atmospheric air heat, which together exceed 50% throughout the heating period. At a collector area of 4 m², their share is the highest compared to other areas (1, 2, and 10 m²). The contribution of atmospheric air heat during the heating period (October–March) significantly exceeds that of solar radiation.

The “HP–microclimate” subsystem operates within defined and well-known temperature limits. It has been established that a heat pump with a compressor power of 1 kW can maintain an indoor temperature for livestock within the range of +5 to +25°C for 6 cows. In the calculations, it was assumed that one cow emits up to 0.7 kWh of heat, the heat pump heats water from 14 to 40°C, the heat pump coefficient of performance (COP) is 3–5, cooling capacity is 2–4 kWh, and heating capacity is 3–5 kWh. It has been determined that the annual energy production, with an average daily animal occupancy time of 15 hours, amounts to 14,000 kWh per kW. The economic effect is estimated at $630 per kW.

The “HP–milk cooling” subsystem, with a heat pump compressor power of 1 kW, ensures milk cooling from +35 to +5°C within a period of up to 3 hours. The average coefficient of performance is 3–4. The volume of cooled milk is 200 liters, and the volume of heated water is 250 liters with a temperature range of 14 to 40°C. The annual electrical energy savings amount to up to 10,800 kWh.

5 Conclusion

In this work, the heat pump system was considered as an effective solution for the utilization of renewable energy sources. The main novelty lies in the integration of the heat pump with alternative heat sources (air, ground, and water), which makes it possible to significantly increase energy efficiency compared to conventional heating systems. The use of modern control technologies and optimization of operating modes ensures stable performance even under changing climatic conditions.

The obtained results show that the use of the heat pump system makes it possible to generate 3–5 times more thermal energy compared to the consumed electrical energy (coefficient of performance COP = 3–5 and higher). This leads to a significant reduction in energy consumption and operating costs. In addition, the system contributes to the reduction of carbon dioxide emissions and the minimization of negative environmental impacts.

The main advantages include high energy efficiency, environmental friendliness, versatility of application, the ability to operate in various climatic conditions, and reduced dependence on fossil fuels. Despite higher initial investment costs, the system pays back through energy savings in the long term.

The application areas of heat pump systems include residential buildings, commercial and administrative facilities, industrial sites, domestic hot water systems, as well as facilities with high energy efficiency requirements. Their use is particularly relevant in regions with high costs of conventional energy carriers and in sustainable development projects.

Thus, heat pump systems represent a promising direction in energy engineering, providing efficient and environmentally safe utilization of renewable energy sources.

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