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Paper

PAPER

RESEARCH OF THE HEAT BALANCE OF AN AUTONOMOUS UNDERFLOOR HEATING SYSTEM WITH A PCM ACCUMULATOR

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Abstract

As a result of the depletion of traditional fuel and energy sources in the world and the increase in the burden on the environment, the issue of saving and efficient use of natural fuel and energy resources is becoming one of the urgent problems on a global scale. Special attention is also paid to the issue of providing households with autonomous heat supply systems using sustainable energy resources in conditions of a sharply continental climate. In this article, the authors have developed a heating scheme for a rural model house with an heat pump unit (HPU) and a warm floor heating system with a heat accumulator. The heat balance equation for the developed rural model house with an HPU and a warm-floor heating system with a heat accumulator was developed using thermal engineering and heat-exchange methods. The calculations were carried out using the Matlab Simulink software package. The results of numerical modeling using the Matlab Simulink software package showed the need to determine the optimal ratio between heat sources and heat losses to ensure a stable microclimate in the room in the range of 20÷24 °C.

Key words: model rural houses, autonomous heat supply system, underfloor heating system with heat accumulator, heat pump device, heating season, sharply continental climatic conditions.

Introduction

Introduction In the present era, the depletion of conventional fuel–energy resources and the increasing anthropogenic pressures on the environment have made the issues of conserving natural fuel reserves and using them efficiently a globally significant challenge. To overcome the existing problems in the fuel and energy supply sector, many countries around the world are compelled to reform their energy infrastructure and widely adopt environmentally friendly, renewable-

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energy-based technologies, including solar-assisted heat pump (SAHP) systems [1]. Against the backdrop of a sharply continental climate and global climate change, ensuring the stable and energy-efficient operation of autonomous heating systems in residential buildings is becoming increasingly important. Autonomous fuel and energy supply systems integrate heat, hot water, and electricity sources into a unified, interconnected configuration. Such systems must remain reliable and capable of continuous operation even during emergencies, fuel shortages, or grid interruptions [2-4]. Several challenges inherent in existing heat supply systems — including daily and seasonal fluctuations in energy loads, the low exergy efficiency of conventional technologies, and reduced performance under extreme cold or high-temperature climatic conditions — necessitate the development of new approaches to modern energy systems [5-6]. Methods and materials. The use of solar heat pump hybrid systems as a solution to these problems is a promising direction. Such systems are based on the optimal combination of heat pump and solar energy technologies, taking into account the potential of renewable energy sources in the region and low-potential heat sources. As a result, they can provide high energy efficiency, environmental safety, and the ability to operate autonomously, which can significantly increase the stability of energy supply systems in the future [7].

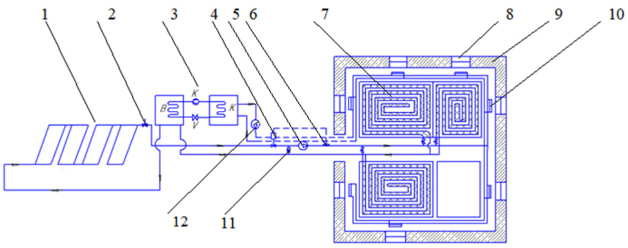

Рис. 1. Figure 1. Thermal diagram of the HPU and heat accumulator underfloor heating system of rural model houses. 1-series-connected solar collector, 2, 11-adjustment valve, 3-heat pump device, 4-thermostat valve, 5,12-circulation pump, 6-heat sensor element, 7-heat accumulator underfloor heating system, 8-window, 9-rural model house, 10-heating radiators.

The integrated heat supply system of model rural houses with a solar-assisted heat pump (SAHP) and a thermal-storage underfloor heating system combines the following three subsystems:

Solar collector–thermal storage–underfloor heating system: 1 – series-connected solar collectors; 2, 11 – control valves; 4 – thermostatic valve; 5 – circulation pump; 6 – temperature sensor; 7 – thermal-storage underfloor heating system.

Heat pump–based heating system:

3 – heat pump unit; 12 – circulation pump; heating radiators. The operation sequence of the integrated heat supply system for model rural houses is as follows:

Under solar irradiation, the water in the series-connected solar collectors (1) is heated to a temperature of 70–80 °C. The flow rate of the heated water is regulated by valve (2). Using the circulation pump (5), the hot water is circulated through the thermal-storage underfloor heating system (7). While circulating in the underfloor heating system, the hot water heats both the indoor space and the thermal storage medium through convective heat transfer. Paraffin is used as the thermal storage material, operating in charging mode during daytime and in discharging mode during the evening. The water returning from the underfloor heating system passes through the evaporator of the heat pump unit (3) and is then directed back to the series-connected solar collectors, thus completing the solar-collector/thermal-storage/underfloor heating cycle. In the evening mode, this solar-based subsystem is switched off.

In the heat-pump-based heat supply system, the return water entering the evaporator of the heat pump unit (3) at 35–45 °C heats the refrigerant (freon), causing it to evaporate. The formed vapor is compressed in the compressor and then delivered to the condenser of the SAHP. In the condenser, the vapor condenses while transferring heat to the circulating working medium — water — driven by circulation pump (12). After passing through the expansion valve, the refrigerant evaporates again in the evaporator, continuing the cycle.

In the heat supply system, water is heated to 65–80 °C in the condenser of the heat pump and is circulated by a pump through the heating radiators, where it releases heat to the indoor environment, thereby completing the heating cycle.

The structural layout of the thermal-storage underfloor heating system is shown in Fig. 2.

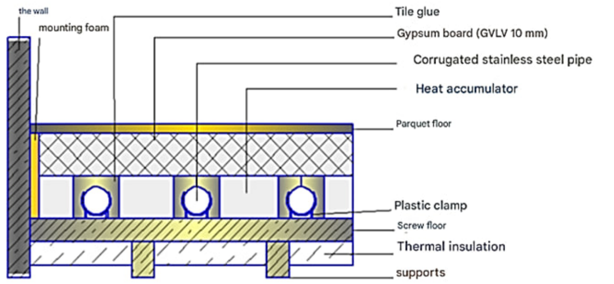

Рис. 2. Figure 2. Scheme of a warm floor heating system with a heat accumulator.

Results and discussion

We calculate the heat balance of the HPU and heat accumulator underfloor heating system of rural model houses based on the following equations [8–11]. The heat balance condition is expressed as $Q_{giv} = Q_{sp}$ (1).

Since the heat for the HPU and heat accumulator underfloor heating system of rural model houses is supplied through the solar collector (SC) and HPU, the value of Q_{giv} can be written as $Q_{giv} = Q_{coll} + Q_{cond} = \eta_{coll} \cdot F_{coll} \cdot q_r^{\Sigma} + g_{fr} \cdot (h_{en.f} - h_{out.f})$ (2).

Alternatively, the same relation can be expressed as $Q_{giv} = Q_{coll} + Q_{cond} = g_{coll} \cdot c_p(t_{out} - t_{en}) + g_{cond} \cdot c_p(t_{out} - t_{en})$.

Here, Q_{coll} is the amount of heat supplied by the solar collector (W); Q_{cond} is the amount of heat supplied by the HPU condenser (W); η_{coll} is the solar collector efficiency (

The total heat demand of the system is defined as $Q_{sp} = Q_{con} + Q_{in} + Q_{h.fl} + Q_{PCM} + Q_{ven} + Q_{inf} + Q_{wall}$ (3).

Accordingly, the transient thermal balance of indoor air can be written as $C_{air}, \frac{dT_{air}}{d\tau} = Q_{con} + Q_{in} + Q_{rad} + Q_{h.fl} + Q_{PCM} - Q_{ven} - Q_{inf} - Q_{wall}$ (4).

Here, C_{air} is the specific heat capacity of indoor air (J/kg·°C); $\frac{dT_{air}}{d\tau}$ is the time derivative of indoor air temperature (K/s); Q_{con} is the convective heat exchange within the indoor environment of the rural model house (W); Q_{in} is the heat released from internal sources (W); Q_{rad} is radiative heat exchange (W); $Q_{h.fl}$ is the heat transferred from the heated floor (W); Q_{PCM} is the heat transferred from the phase change material (PCM) (W); Q_{ven} is the heat loss due to ventilation (W); Q_{inf} is the heat loss caused by infiltration through walls, ceiling, and floor (W); and Q_{wall} is the heat loss through the wall structures of the model house (W).

From these relations, the indoor air temperature variation can be expressed as $C_{air}, \frac{dT_{air}}{d\tau} = \frac{Q_{con} + Q_{in} + Q_{rad} + Q_{h.fl} + Q_{PCM} - Q_{ven} - Q_{inf} - Q_{wall}}{\rho_{air} c_p V_{air}}$ (5).

Equation (5) represents the dynamic thermal balance of the indoor microclimate of rural model houses. It describes the time-dependent variation of indoor air temperature as a function of the difference between incoming and outgoing heat fluxes. This equation serves as the fundamental physico-mathematical model for evaluating the energy efficiency of the heating system during the heating season, simulating the temporal stabilization of microclimate parameters, and analyzing the influence of underfloor heating, phase change materials (PCM), heat transfer processes, and heat losses on the overall thermal balance.

The thermo-physical parameters of air, expressed by $\rho_{air} c_p V_{air}$, determine the thermal capacity of the indoor environment. A higher thermal capacity leads to a slower rate of temperature variation, allowing a more accurate assessment of heat transfer control, system response time, and overall energy losses.

Figure 1 presents the results obtained in MATLAB based on Equation (5).

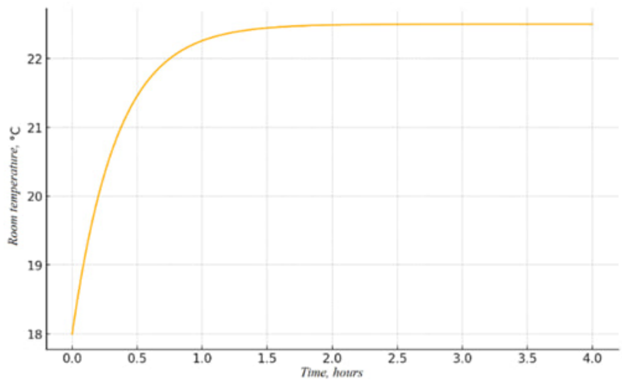

Рис. 3. Figure 3.Dynamic variation of indoor temperature in model rural houses.

Conclusions

The research results show that, in controlling the indoor microclimate of model rural houses, the combined effects of convective and radiative heat transfer, underfloor heating, phase change materials (PCM), and internal heat sources, along with ventilation, infiltration, and structural heat losses, constitute the primary factors determining the dynamic variation of indoor air temperature. The proposed differential heat balance equation enabled the calculation of indoor temperature variation over time with accuracy close to real operating conditions.

Numerical simulations performed using MATLAB/Simulink demonstrated that maintaining a stable indoor microclimate within the range of 20–24 °C requires determining the optimal balance between heat sources and heat losses. This approach is crucial for reducing energy consumption, minimizing heat losses, and improving the overall efficiency of the heating system. The advantage of the developed model lies in its ability to regulate heating system parameters, assess the thermal inertia effects of underfloor heating and PCM, and serve as an effective tool for developing energy-efficient heating strategies for rural houses.

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