ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 11, Issue 10, October 2024

Selection of Rational Heat Carriers and Thermal Accumulators in a Hybrid Heating System for a Rural House

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ABSTRACT. Currently, one of the important tasks in creating an optimal microclimate in rural model houses is providing heat to the object. Autonomous hybrid heat supply systems are one of the solutions to this problem. Recently, autonomous hybrid heating systems are increasingly being considered as an alternative to central heating systems. Therefore, it is important to choose optimal heat carriers and energy-efficient heat accumulators in hybrid heat supply systems. In this work, the thermophysical properties of various heat-accumulating materials were studied using thermodynamic analysis, thermal engineering and experimental methods. In the table and figure, it can be seen that the amount of heat, depending on the water flow mode, is higher relative to the pyrolysis liquid and waste oil.

I. INTRODUCTION

Currently, the reforms being implemented in our country are aimed at improving energy efficiency and savings, which not only allow for increased production but also enable significant savings in fuel and energy resources. The decree of the President of the Republic of Uzbekistan dated June 14, 2024, No. UP-222 “On Additional Measures to Enhance the Efficiency of Energy Resource Use” emphasizes the need to achieve savings in natural fuel and energy resources, the widespread implementation of renewable energy sources, the enhancement of energy resource efficiency, and the use of composite thermal insulation building materials to improve the energy efficiency of buildings [1].

It is important to create a hybrid heat supply system based on alternative energy sources, to increase energy efficiency and reduce the negative impact on the environment. A hybrid heat supply system is a system designed to provide heat by combining different energy sources (for example, solar, biomass, gas). These systems are usually designed with local conditions, energy requirements, and economic considerations in mind. Creating a hybrid heat supply system based on alternative energy sources allows for increased energy efficiency and is economically profitable without harming the environment. Such systems meet modern energy requirements and play an important role in achieving sustainable development goals [2-4].

As a solution to these priority tasks, important parameters for reducing energy consumption in buildings include the introduction of scientific and technological innovations in various sectors of the economy and social facilities. This is related to using energy-efficient building materials with improved thermal characteristics, highly effective heat carriers, and thermal accumulators in heating systems.

Energy savings in heating systems are connected to the creation of new types of materials that accumulate heat, which are used to store heat in the walls and floors of buildings and structures. As a result, this will lead to the development of research and production of energy-saving building materials and heat-accumulating systems.

A promising and economically viable direction in the production of thermal energy storage materials is the development of materials for accumulating latent energy, such as phase change materials (PCMs). These materials store heat during a phase change (for example, from solid to liquid) and release it during the reverse process [5].

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II. METHODS AND MATERIALS

In this study, the thermal-physical properties of various thermal storage materials were examined using thermodynamic analysis, heat engineering methods, and experimental techniques. The goal of the research is to select the type of energy-saving thermal storage material for underfloor heating systems in typical rural houses and to investigate its thermal-physical properties [6].

The selection process of heat carrier and heat accumulator in hybrid heat supply systems is based on a number of criteria. These criteria play an important role in ensuring the effectiveness, economic aspect, and long-term operation of the system.

1. Heat Carrier Selection Criteria
Heat Capacity:
High specific heat capacity (for example, 4.18 kJ/kg·°C in water) allows efficient storage and transport of heat energy.
Adaptability to Climatic Conditions:
The heat-carrying material must be suitable for the climatic conditions. For example, in cold regions, antifreeze compounds may be needed.
Chemical Stability:
It is important that the carrier material does not lose its properties at high temperatures and does not change its chemical composition.
Toxicity and Ecological Effects:
Carrier materials must not harm the environment and be safe for human health.
Price and Competitiveness:
The cost and availability of carrier materials affect the total cost of the system.

2. Heat Accumulator Selection Criteria
Storage Capacity:
The ability of the accumulator to store heat depends on its material and design. Materials with high heat capacity should be selected.
Heat Redistribution Rate:
It is important to be able to quickly remove heat during charging and use of the battery.
Thermal Losses:
The degree of insulation of the accumulator and the ability to minimize thermal losses increase the efficiency of the system.
Long-Term Performance:
The battery materials must be capable of long-term operation, and resistance to temperature changes.
Technological Convenience:
It should be easy to integrate into the accumulator system and convenient to manage the operations.

3. General Rules
Flexibility: Systems should be able to adapt to the use of different energy sources, as well as allow for the addition of additional modules in the future.
Economic Efficiency: Considering the costs and energy efficiency of both components.
Management and Monitoring: The system is equipped with modern management and monitoring systems to increase its efficiency.

Choosing the best heat carrier and heat accumulator in hybrid heat supply systems is one of the most important factors affecting the overall efficiency, economic aspects, and long-term performance of the system. Compliance with these criteria will help to achieve high efficiency and minimize costs [7].

The following table presents the materials used for thermal energy promising and economically viable approach in the production of thermal energy storage materials is the development of phase change materials (PCMs) that accumulate latent energy. These materials store heat when undergoing a phase change (for instance, transitioning from solid to liquid) and release it during the reverse process [8].

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Table 1.
Thermophysical characteristics of heat accumulator materials

Types of heat accumulator	Melting point, °C	Heat of fusion, Dj/g	Heat capacity, kDj/(kg K)	Thermal conductivity, W/(m K)	Density, kg/m^3
Water	0	334	4,18÷4,2	0,58	1000
Waste oil	-40	150÷180	1,7÷2,5	0,12÷0,15	875÷895
Paraffins	18÷60	50÷250	2,0÷2,8	0,2	750÷900
Salt hydrates	20÷120	200÷350	1,9÷2,5	0,5÷1	1500÷1600
Oil mixtures	-10÷100	120÷220	1,5÷3,0	0,4÷0,7	1100÷1600
Pyrolysis liquid	50÷120	100÷150	2,5÷3,4	0,1÷0,2	1100÷1200

In recent years, in the construction of typical rural houses, along with heating systems, underfloor heating systems have also been used, which are used as a supplement to traditional heating systems to create comfortable conditions in typical rural houses. The use of underfloor heating allows for a more even distribution of air temperature in the room compared to traditional heating systems.

The use of underfloor heating in a hybrid heating system for typical rural houses creates the most comfortable conditions in the room since this system ensures that the air temperature in the lower part of the room will be 3-6 ℃ higher than in the upper part. This temperature distribution is considered more natural and comfortable for the human body and does not cause a feeling of overheating.

Thus, the temperature distribution is considered more natural and comfortable for the human body and does not cause a feeling of excess heat. In typical rural houses, the installation of underfloor heating systems requires a design based on SNiP. When designing, the floor surface temperature must meet certain requirements, and in living rooms, the floor surface temperature with an underfloor heating system should not exceed 25 ÷ 26 ℃. To calculate heat exchange processes in a heating system with warm floors in typical rural houses, a design diagram of a heating system with warm floors was developed (Figure 1).

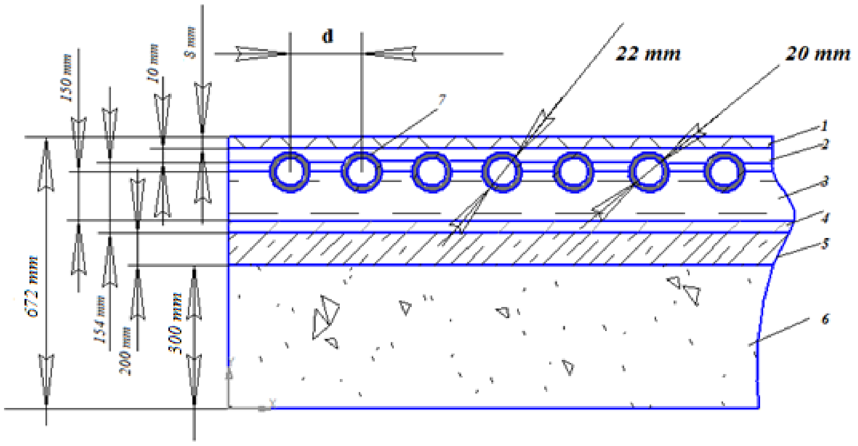

Fig. 1. Structural diagram of a heating system with warm floors of a typical rural house:
1-laminate, 2-segment screed, 3-paraffins, 4-metal box for storing paraffin, 5-polystyrene foam, 6-warm floor slab, 7-warm floor system pipes.

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International Journal of AdvancedResearch in Science, Engineering and Technology
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By the design scheme of the heating system with warm floors in exemplary rural houses (Figure 1), a 0.2 m thick layer of expanded polystyrene is laid on a 0.3 m thick reinforced concrete slab, a 0.154 m thick metal shell is installed on it, inside which paraffin with a thickness of 0.150 m is placed. A 0.01 m thick layer of cement concrete is poured on top of the metal shell, in which metal heating pipes with an external diameter of 0.022 m are installed. The metal pipes are connected to the paraffin layer, and the upper part is connected to the cement concrete through the metal shell. A typical rural house with a total area of 144 m² consists of one living room with an area of 31.9 m², one bedroom with an area of 31 m^2, one kitchen with an area of 18 m2, one children's room, as well as a hallway with an area of 22.4 m² and a bathroom with an area of 6.4 m^2. Figures 2 and 3 show the general layout of the house (standard design) and the basic diagrams of the heating system with warm floors for a typical rural house.

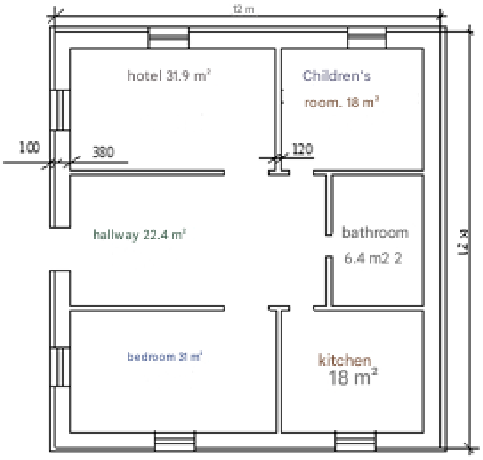

Fig. 2. Layout of a rural house with a total area of 144 m² (standard design).

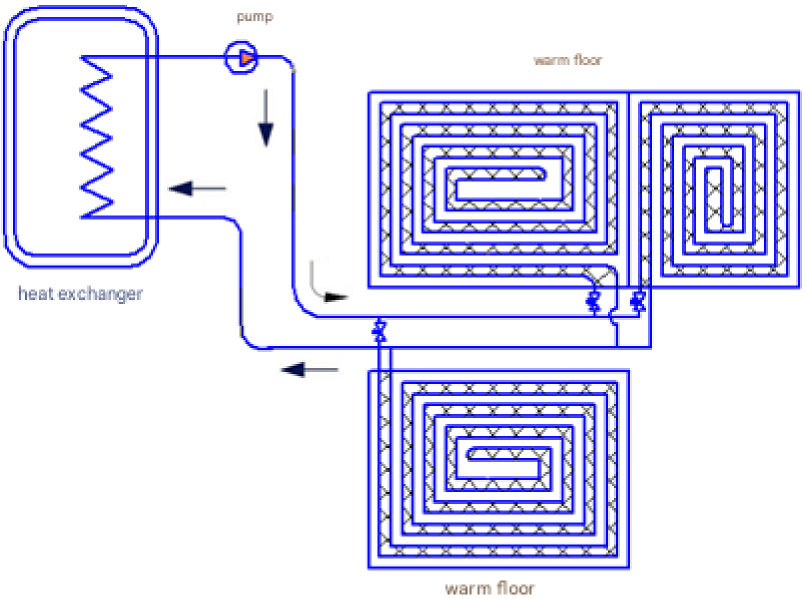

Fig. 3. Schematic diagram of a heating system with warm floors in a typical rural house.

III. RESULTS

We calculate convective and conductive heat transfer processes depending on the fluid flow mode and the design features of the pipeline. In this case, we consider two main flow modes: laminar and turbulent, and also take into account the

ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
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conditions of heat exchange between the pipe walls and the fluid flow inside. The heat exchange surface for a given underfloor heating pipe is determined by the formula:

$$F = \frac{\pi d^2}{4} = \frac{3{,}14 \cdot 0{,}015^2}{4} = 0{,}0002, m^2$$

We determine the speed of movement of the coolant using the formula:

$$G_w = \frac{G_m}{\rho_w} = \frac{0{,}1}{1000} = 0{,}0001, \quad \frac{m^3}{s}$$

where, $G_m -$ water consumption, $G_m = 0{,}1\ \frac{kg}{s}$; $\rho_w -$ density of heat carriers at average temperatures, $\rho_w = 1000\ \frac{kg}{m^3}$.
We determine the average speed of the coolants using the following formula.

$$w = \frac{G_w}{F} = \frac{0{,}0001}{0{,}0002} = 0{,}5, \quad \frac{m}{s}$$

We determine the flow mode for heat carriers based on the value of the Reynolds criteria.

$$Re = \frac{w \cdot d}{v^2} = \frac{0{,}5 \cdot 0{,}015}{1 \cdot 10^{-6}} = 7\,500 < 10^4$$

where, $w -$ average speed of the coolant, $\frac{m}{s}$; d- diameters of underfloor heating pipes, m; v^2 −kinematic viscosity of the coolant, for water, $v^2 = 1 \cdot 10^{-6}\ \frac{м^2}{c}$.
Considering the complexity of the factors influencing the heat exchange process in pipes, empirical dependencies obtained on the basis of generalization of experimental data are often used for practical calculations. One of such approaches is the use of formulas proposed by M.A. Mikheev [5], who derived generalized formulas for calculating the criteria of convective heat exchange in pipes and channels at l/d>50.a) для ламинарного течение жидкостей при $Re < 2000$:

$$Nu = 0{,}15Re^{0{,}33}Pr^{0{,}43}Gr^{0{,}1}\left(\frac{Pr_в}{Pr_{ст}}\right)^{0{,}25}, \quad (1)$$

a) for a developed turbulent regime, the flow of liquids at $Re > 10^4$:

$$Nu = 0{,}021Re^{0{,}8}Pr^{0{,}43}\left(\frac{Pr_в}{Pr_{ст}}\right)^{0{,}25}. \quad (2)$$

For the transitional flow regime (Reynolds number Re in the range from 2000 to 10000), when the flow is unstable and can be partly laminar, and partly turbulent, the results of different experiments can vary greatly. In such conditions, an accurate calculation of heat transfer is difficult. However, for an approximate estimate of heat transfer in the transitional regime, M.A. Mikheev proposed the following formula:

$$Nu = APr^{0{,}43}\left(\frac{Pr_в}{Pr_{ст}}\right)^{0{,}25}. \quad (3)$$

where the value of A depends on the Re number and is given in Table 2:

Table 2
Value of coefficient A.

$Re \cdot 10^{-3} = 2{,}1$	2,2	2.3	2,4	2,5	3	4	5	6	8	10
A=1,9	2,2	3,3	3,8	4,4	6	10,3	15,5	19,5	27	33,9

In the experiments conducted, the air temperature inside the typical rural house was taken to be 22℃, and the floor surface temperature was 26℃.
Tables 3-4 show the results of experiments on the heat transfer coefficient, convective heat exchange and the amount of heat transferred for hot water moving in the pipes of a warm floor in laminar and turbulent flow modes.

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Table 3.
Calculated and experimental data for determining the heat transfer coefficient in the GST (heat carrier - water).

№	w, m/s	Re	Nu	$\alpha, \frac{W}{(m^2 \cdot °C)}$	$q, \frac{W}{m^2}$	Q, W
1.	0,5	7500	37,33	1443,422	5773,686	20443,24
2.	0,6	9000	54,43	2104,602	8418,407	28306,03
3.	0,7	10500	55,56	2148,528	8594,1106	36785,13
4.	0,8	12000	61,83	2390,752	9563,0075	40932,28
5.	0,9	13500	67,94	2626,979	10507,914	44976,73
6.	1,0	15000	73,91	2858,002	11432,008	48932,11

Table 4.
Results of calculation and experimental studies to determine the heat transfer coefficient (heat carrier - pyrolysis liquid).

№	w, m/s	Re	Nu	$\alpha, \frac{W}{(m^2 \cdot °C)}$	$q, \frac{W}{m^2}$	Q, W
1.	0,5	6250	372,2172	372,2172	1488,869	7012,571
2.	0,6	7500	515,3776	515,3776	2061,51	9709,714
3.	0,7	8750	647,0852	647,0852	2588,341	12191,09
4.	0,8	10000	1270,607	1270,607	5082,426	23938,23
5.	0,9	11250	1396,153	1396,153	5584,613	26303,53
6.	1,0	12500	1518,935	1518,935	6075,739	28616,73

In the table and figure, it can be seen that the amount of heat, depending on the water flow mode, is higher relative to the pyrolysis liquid and waste oil.

IV. CONCLUSION

Creating a hybrid heat supply system based on alternative energy sources allows to increase energy efficiency and be economically profitable without harming the environment. Such systems meet modern energy requirements and play an important role in achieving sustainable development goals.

Choosing the best heat carrier and heat accumulator in hybrid heat supply systems is one of the most important factors affecting the overall efficiency, economic aspects, and long-term performance of the system. Compliance with these criteria will help to achieve high efficiency and minimize costs.

A thorough understanding of the theoretical principles governing heat carriers and thermal accumulators is essential for designing an efficient hybrid heating system for a rural house. The choice of materials and system design will significantly impact the overall performance, energy efficiency, and sustainability of the heating solution.

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