Thermal efficiency of the enclosing structures of an individual residential house in conditions of interconstant thermal energy generation

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Abstract. The involvement of recycled wood resources and low-quality wood in the processing provides an active source of raw materials for the construction industry. Environmentally friendly building materials in the form of wood-mineral composites (WMC) help recycle this waste and help conserve natural resources. The study examined the thermal performance of enclosing structures in the form of a frame wall filled with mineral wool, walls made of aerated concrete blocks and stands made of WMC. The purpose of the work was to determine the thermal regime of enclosing structures under stationary and non-stationary thermal conditions. The unsteady mode was created by simulating the generation of thermal energy for 10 hours a day. The mode corresponds as closely as possible to the actual operating conditions of an individual housing construction project, provided that it is heated by a solid fuel boiler or stove with periodic generation of thermal energy. The total simulation time is 5 days. It has been established that in a stationary thermal mode, all considered structures comply with sanitary and hygienic requirements and heat conservation standards.

1 Introduction

Population growth, intensive development of the consumption market, and an increase in industrial production volumes inevitably lead to increased education and accumulation of household and industrial waste. These phenomena occur against the backdrop of a gradual depletion of mineral reserves, a decrease in biological diversity, and an increase in the degree of exploitation of forests. Industrial and household waste require constant attention and the introduction of recycling technologies to reduce overall costs and negative environmental impact. Priority technologies for processing certain types of waste depend on the availability and production capacity of the mining and processing industries of a particular territory, country or region, as well as on the current level of resource consumption, production culture and environmental requirements.

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Significant volumes of forest resources are concentrated in the Russian Federation. This is about 20% of the total forest area on the planet or in absolute terms – more than 800 million hectares [1]. Every year in Russia logging is carried out in volumes exceeding 200 million m^3 (224.945 million m^3 in 2021). The country is one of the 10 leading countries in logging. Russia is in 4th place in the production of lumber in the world. The Krasnoyarsk Territory and the Irkutsk Region are the leading regions of Russia in terms of timber harvesting (24.7 and 32.7 million m^3 were harvested in 2021, respectively), occupy a leading position in the Russian forestry sector and have a fairly developed forestry industry. At the same time, the Krasnoyarsk Territory and the Irkutsk Region have 24% of the total forested area of all of Russia (190 million hectares out of 809 million hectares). Developed logging and processing technology leads to the formation of significant volumes of secondary raw materials and waste. According to expert estimates, up to 75 million m^3 of wood waste is generated annually in the Russian timber industry. In this case, no more than 48...55% is processed. Thus, at least 35 million m^3 of waste and secondary raw materials do not generate income, effort and money are spent on their disposal, their very presence worsens the situation associated with fire danger, and there is also a negative impact on the environmental situation. The lion's share of wood waste (slabs, sawdust, slats) is transported to landfills and landfills, which occupy significant areas and periodically burn. This leads to constant fire hazards, since such waste is capable of spontaneous combustion. According to [2], a significant part of the total volume of waste in the Russian Federation (up to 50%) is waste of organic origin, and up to 40% of it does not fall into processing and recycling programs, but ends its life cycle in landfills. In absolute figures for the Russian Federation, this is over 90 million m^3 of total volume of low-quality wood, 12.7 million m^3 of sawmill waste, and more than 1 million m^3 of sawdust [3].

It is a well-known fact that the construction sector is the largest consumer of resources [4,5]. The main direction of improving building materials is the replacement of natural fossil materials with products of processing and waste disposal. In this area, the development of composite materials based on mineral hydrated binders and various fillers, including organic ones, is underway.

Wood-mineral composites can become a technology that will ensure the involvement of the above-mentioned resources in industrial production. Such composites, in the case of the production of building materials (wood concrete, sawdust concrete, fiberboard) can be used as thermal insulation, structural and finishing materials. Incorporation of solid waste into conventional concrete as a partial replacement for fine aggregate provides environmentally friendly and efficient disposal along with improved thermomechanical properties of cementitious composites [6]. There are many known works by domestic and foreign authors in the field of building materials from wood-mineral composites [7-11]. Basically, the work sets the task of improving the technology of building materials - substantiating the possibility of partial replacement of mineral components with organic ones to improve the thermal performance of buildings. The thermal efficiency of buildings made of materials based on wood-mineral composites depends on many factors, the design solutions used, the shape and size of the blocks, joint materials, and the presence of thermal inhomogeneities [12,13]. In [14], the authors carried out mathematical modeling of heat transfer phenomena in the wall of a building. It has been established that walls with a high degree of thermal inertia are a good passive means of increasing thermal comfort in dry and hot climates. The results showed that the solid wall reduces the amplitudes of indoor temperature changes when outdoor temperatures fluctuate. The choice of building materials plays an important role in reducing air conditioning costs. At the same time, the importance of adequate choice of both material and wall design is acute in countries with relatively cold climates.

Most works consider a residential building under stationary thermal conditions. This mode is easy to obtain provided there is a constant source of thermal energy, for example a centralized heating system or an automated boiler running on main gas. However, there are a significant number of territories with a very harsh climate that do not have mains gas or other stable energy sources, the operation of which with thermal generation can be automated and reduced to a stationary mode. If we consider the territorial features of gasification in Russia, it turns out that the lion's share of facilities are gasified in the European part of the Russian Federation and in the Urals. There is practically no main gas in Siberia, and the population mainly heats itself with coal and wood.

The conditions for thermal generation of a building are closely related to the mode of stay of people in them. In fact, a person spends at least 12 hours a day at work, on the road, i.e. outside a residential property. Thus, the operating time of boilers and furnaces, subject to supervision, does not exceed 10 hours a day. For the remaining 14 hours, the home cools down due to heat exchange with the environment. Those the enclosing structures of the dwelling will operate in the mode of non-stationary heat transfer. In the absence of constant generation of thermal energy, the temperature of the enclosing structures will gradually decrease, and a dew point and even freezing may form. The rate of decrease in internal temperature is influenced by the ratio of the calculated thermal loads for heating, the massiveness of the walls and the ambient temperature.

2 Purpose and objectives of the study

Determine the influence of the massiveness of the walls on the thermal regime of the room with intermittent generation of thermal energy.

Research objectives:

- Justify competing technologies for affordable low-rise construction for rural and forest areas;
- Determine the thermal regime of the object under conditions of non-stationary thermal regime caused by periodic generation of thermal energy.

Technologies for individual low-rise housing construction in the Russian Federation are distinguished by a wide variety of wall materials and design solutions used. The absence of strict regulation, standardization and the essentially declarative, rather than permissive, nature of interaction with supervisory authorities allows the individual developer to build as he wants and from what he can. Typically, locally available building materials are widely used. Until recently, wooden houses built using timber technology, as well as the technology of using round rounded logs, were the most widespread. Rising prices for these building materials make such structures inaccessible. An important factor is the increase in housing maintenance costs caused by rising energy prices and very harsh climatic conditions. Therefore, a modern individual developer relies on inexpensive and highly efficient materials and design solutions in the field of heat conservation. In the Siberian Federal District, frame houses, as well as buildings made of small-format blocks (aerated concrete, foam concrete, wood concrete) are widely used for individual housing construction. Determining factors are the availability of materials, as well as the availability of workers familiar with the technology. The developer wants to obtain a facility with high thermal performance, capable of providing a good microclimate and sanitary conditions.

The thermal insulation qualities of walls in terms of thermal energy consumption are determined by the magnitude of the heat flow passing through the fences, or its inverse value of heat transfer resistance. Sanitary and hygienic conditions in premises in winter largely depend on the temperature of the inner surface of the outer wall. The surface temperature should be limited by the condition of minimal heat transfer from the human body to the outer wall, as well as by the condition of the absence of condensation on the surface of the fence. The temperature of the inner surface of the enclosing structure must not be lower than the dew point. Since the generation of thermal energy will be associated with the operation of heating equipment for no more than 10 hours a day, enclosing structures must have a certain thermal inertia. The thermal inertia of a material is directly proportional to its density. On the other hand, materials with high density have low thermal insulation properties. A rational combination of these mutually exclusive indicators will allow us to obtain a residential property with high performance indicators. Researchers [15] considered the thermal inertia of foam concrete. It was found that the thermal inertia of foam concrete is lower than that of concrete, and it was proposed to combine foam concrete with a material with a higher thermal mass in order to increase the reduction in the amplitude of temperature fluctuations of the structure.

High-density concrete has high thermal conductivity; by adding low-density materials, such as sawdust, an optimal ratio of mass and thermal conductivity can be obtained. In [16], it is substantiated that adding wood chips to sand concrete allows one to reduce thermal conductivity from 1.20 to 0.55 W/(m·^{0}C) while simultaneously reducing density from 2100 to 1400 kg/m^3.

The accumulation of thermal energy by wall material makes it possible to obtain a balance between the production and loss of thermal energy in non-stationary modes. Heating an individual residential property with a solid fuel boiler, as a rule, has a pulsating, uneven supply of thermal energy. In work [17], the issues of thermal accumulation were studied to reduce negative phenomena in the absence of a balance between the demand and supply of thermal energy. The higher the thermal storage capacity of the enclosing structure, the less influential fluctuations in the outside air are. With a slow decrease in temperature, before the start of a period of sharp cooling, the temperature distribution in the fence at each moment of time practically corresponds to the stationary one. It has been confirmed that the inertia and thermal diffusivity of the fragments have a certain effect on the temporary displacement of the extrema of heat flows and temperatures on the inner surface. For objects of medium density (expanded clay concrete), such displacements are observed in the interval of 8–12 hours; for a fragment of low density (expanded polystyrene) there are practically no displacements, i.e. There is practically no thermal inertia, for objects made of foam and aerated concrete - within 3–8 hours [18]. The heat absorption coefficient depends on the physical properties of the material, as well as the time period in which the heat flow changes. The standard value of the heat transfer resistance of the enclosing structure for the climatic conditions of the Siberian Federal District (Krasnoyarsk) is R = 3.6 (m^2 ·°C)/W.

3 Materials and research methods

Let's consider three options for individual housing designs that are widely used in the construction market of the Siberian Federal District. This is a frame technology, a technology made from pieced aerated concrete blocks and a structure in the form of a solid monolith made of wood-mineral composite (arbolite).

For multilayer enclosing structures R is determined by the formula

$$R = \frac{1}{\alpha_{in}} + R_c + \frac{1}{\alpha_{ou}} + \frac{\delta i}{\lambda i}, \text{(m}^2 \cdot \text{°C)/W} \quad (1)$$

where α_{ou} – heat transfer coefficient of the outer surface of the wall, α_{ou} = 23 W/(m^2·°C); α_{in} – heat transfer coefficient of the inner surface of the wall, α_{in} = 8.7 W/(m^2·°C); R – thermal resistance of the wall material; δ_i - layer thickness; λ_i – thermal conductivity coefficient.

We accept the condition that the value of heat transfer resistance of competing wall structures (Figure 1) should be close to the standard value. For a frame wall with insulation made of a mineral wool board 150 mm thick and a facing layer of two layers of OSB board 12 mm thick, each R will be determined by:

$$R = \frac{1}{8,7} + \frac{1}{23} + \frac{0,024}{0,18} + \frac{0,15}{0,045} = 3,6 \ (m^2 \cdot °C)/W \quad (2)$$

A wall made of aerated concrete 0.5 m thick (blocks 500×300×600 mm), plastered on both sides with cement-sand plaster 20 mm thick:

$$R = \frac{1}{8,7} + \frac{1}{23} + \frac{0,04}{1} + \frac{0,5}{0,15} = 3,5 \ (m^2 \cdot °C)/W \quad (3)$$

A wall made of wood-mineral composite (monolithic wood concrete) 0.6 m thick, plastered on both sides with cement-sand plaster 20 mm thick:

$$R = \frac{1}{8,7} + \frac{1}{23} + \frac{0,04}{1} + \frac{0,6}{0,2} = 3,2 \ (m^2 \cdot °C)/W \quad (4)$$

Material indicators are given in Table 1.

Table 1. Physical and mechanical properties of materials.

Material	Thermal conductivity coefficient of the material, $W/(m^2 \cdot °C)$	Specific heat capacity, $kJ/(kg \cdot {}^0C)$	Material density, kg/m^3
Mineral wool plate	0.045	0.84	80
OSB	0.18	1.9	650
Arbolit	0.2	2.3	650
Aerated concrete D400	0.15	0.84	400
Plaster TsPS	1.0	1.1	1800
Wood (pine)	0.18	2.3	600

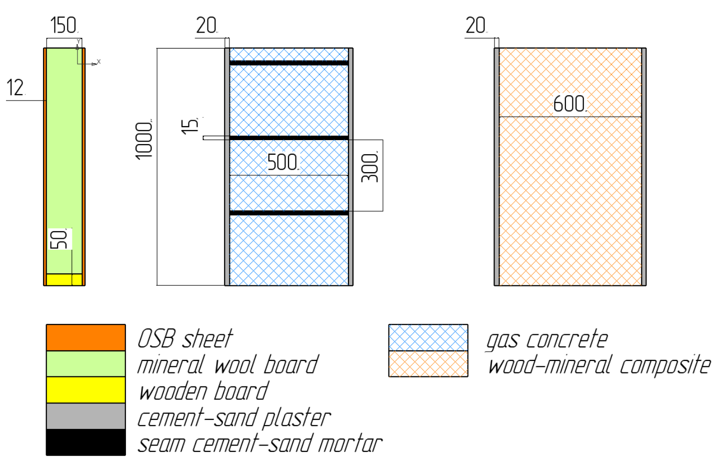

Fig. 1. Wall material options.

When modeling thermal processes, the heat flow is directed normal to the wall surface. Boundary conditions: internal air temperature t_{int} = +20°C; outside temperature: air t_{ext} = -25°C; heat transfer coefficient of the inner surface of the walls (SP 50.13330.2012) α_{si} = 8.7 $W/(m^2 \cdot °C)$; heat transfer coefficient of the surface of the outer wall (SP 50.13330.2012) α_{se}=23 $W/(m^2 \cdot °C)$;

The wall section was modeled in a CAD package and exported to the Elcut solid modeling system [12,19]. The system operates based on the finite element method. Next, a finite element mesh was specified and boundary conditions were assigned. Then the calculation was carried out. In the first part of the study, the problem of heat transfer under stationary conditions was simulated. Those conditions of constant heating of the room were simulated with the calculated value α_{si} = 8.7 W/(m^2·°C). The program determined the heat flow through a certain section using thermal fields (Figure 2).

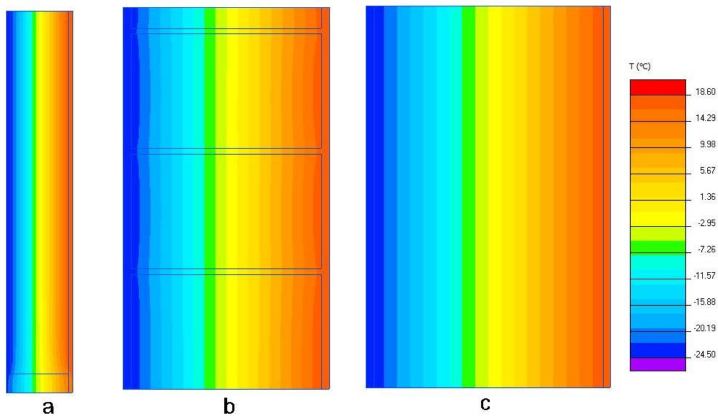

Fig. 2. Thermal fields and temperatures in the Elcut program: a – frame wall; b- aerated concrete; c – wood-mineral composite.

The calculated heat flow is: frame wall - 13.85 W/m^2, aerated concrete wall - 15.65 W/m^2, wood-mineral composite wall - 14.1 W/m^2 (Table 2). From the picture of the thermal field it is clear that seams made of cement-sand mortar have a negative impact on the thermal efficiency of the structure, since the seam material has a thermal conductivity almost seven times higher than the thermal conductivity of the main wall material.

The amount of heat flow can be determined from the relationship:

$$g = \frac{T - t}{R} \text{ (m}^2 \cdot \text{°C)/W} \quad (5)$$

where T is the indoor temperature, °C; t – temperature outside the room, °C.

Based on the obtained values of heat flow and temperature difference:

$$R = \frac{20 - (-25)}{g} \text{ (m}^2 \cdot \text{°C)/W} \quad (6)$$

Table 2. Physical and mechanical properties of materials.

Wall	Heat flow, W/m^2	Calculated value R, (m^2 ·°C)/W (dependence 1)	Value R, (m^2 ·°C)/W (dependence 6)	Deviation, %
Frame wall	13.85	3.6	3.249	10
Wall made of aerated concrete blocks	15.65	3.5	2.875	18
Wood-mineral composite wall	14.1	3.2	3.191	0.3

The deviation for the frame wall is due to the presence of thermal inhomogeneity in the form of a bar of the bottom trim. On a wall made of piece blocks, these are the seams. The data are well verified with work [20]. Thus, in the mode of stationary heat transfer, all types of structures provide normal thermal conditions for the functioning of the room.

In the second part of the work, the problem of heat transfer was simulated under the condition of intermittent generation of thermal energy. Those the operating mode was set to best correspond to the actual conditions of occupants staying in the room and heating with boilers or stoves using solid fuel. The impulse function has been activated in Elcut. The observation interval was set at 5 days or 432000 sec with a slice step of 1 hour or 3600 sec. Initial wall temperature +20°C. Convection mode. Those. The heating conditions of the room were simulated with a calculated value of α_{si} = 8.7 W/(m^2·°C) for 10 hours a day. Subsequently, the generation of thermal energy stopped. This simulated heating a room using a furnace or boiler with intermittent firing.

Figure 3 shows a graph of temperature changes on the inner surface of the wall. The dynamics of temperature changes were recorded over five days or 432,000 seconds.

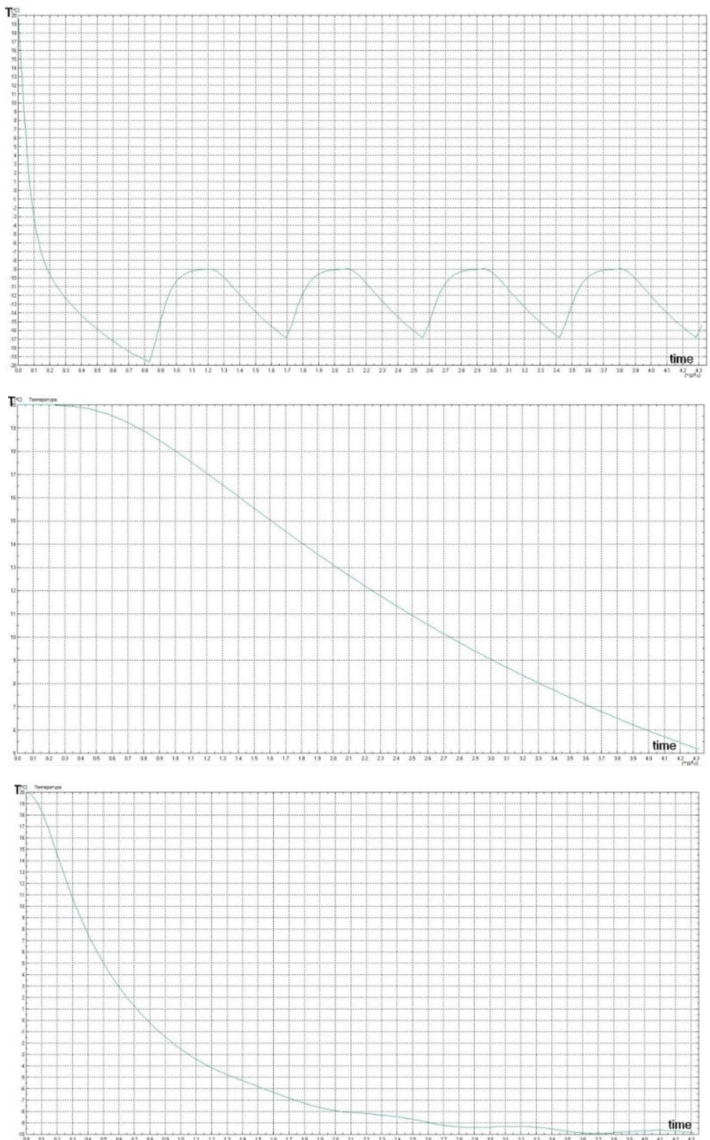

Fig. 3. Dynamics of changes in wall surface temperature (from top to bottom frame wall, aerated concrete block, DMK).

Figure 4 shows the thermal field pattern after 6 hours.

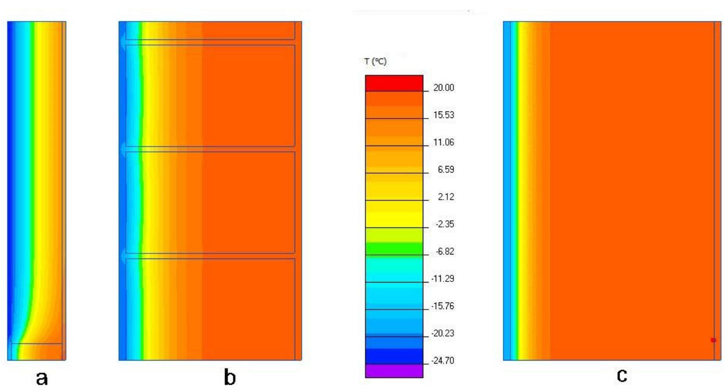

Fig. 4. Thermal fields and thermal isotherms after 6 hours.

4 Results and discussion

A stationary heat transfer mode with a stable constant supply of thermal energy ensures normal operation of the considered elements of the enclosing structure. The obtained values of heat transfer resistance of the enclosing structure from 2.87 to 3.2 (m^2 ·°C)/W generally correspond to the standard values. The surface temperature of the walls of all considered structures meets sanitary and hygienic requirements in terms of dew point formation.

Under the design operating mode with thermal energy generation for 10 hours a day, i.e. the design mode of non-stationary heat transfer, the key point that ensures sanitary and hygienic requirements is the massiveness of the walls. Frame walls under these conditions quickly lose temperature. Under normal humidity and temperature conditions (operation mode A), the dew point formation temperature is +11 °C. According to the graph (Figures 3,4), the temperature of the inner surface of the wall corresponding to the point of dew formation is achieved in 1.4 hours for a frame wall, 8.3 hours for a wall made of aerated concrete blocks. The surface of a wood-mineral composite wall will cool to the dew point in 69.4 hours or 2.9 days.

Consequently, under the considered conditions of thermal energy generation, insufficiently massive frame walls and walls made of aerated concrete blocks do not provide standard sanitary conditions; the structure quickly warms up and also cools down quickly. To ensure the longest possible burning time of solid fuel in the furnace of a boiler or furnace, residents extremely limit the access of air to the supply ash section. At the same time, the speed of the flue gases decreases sharply, and their temperature also decreases. These phenomena inevitably lead to the formation of condensation in chimneys, a decrease in the efficiency of fuel combustion, and an increase in the volume of harmful emissions. When heating with brown coal (namely, these types of coal are mainly mined in the Siberian Federal District), the sulfur contained in the coal intensively mixes with the combustion condensate, which leads to corrosion of the heating system elements.

More massive walls made of wood-mineral composite (WMC), due to the accumulation of thermal energy, intensively store thermal energy when heating is available and “give off” heat to the room when cooling. Under the conditions adopted in the work, and this is an external temperature of -25°C, after 3 days dew will fall even on the walls of the WMC. Consequently, to ensure standard sanitary conditions, it is necessary to either increase the level of thermal generation power or ensure its continuity through, for example, automated boilers and sorted fuel.

5 Conclusion

Considering the enclosing structures of individual housing construction projects, the main factor, the priority purpose of specific design solutions is the availability, low cost and high thermal efficiency of the materials used. The work examined frame technology, small-block construction from aerated concrete blocks and massive walls made from wood-mineral composite.

Using simulation modeling methods, thermal efficiency indicators were determined under stationary and non-stationary conditions. In non-stationary conditions with heat generation 10 hours a day, structures in the form of frame walls and aerated concrete blocks have unsatisfactory sanitary and hygienic indicators, since the wall surface temperature is below the dew point temperature.

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