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Passive Solar Heating: How to Control the Heating Regime

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ABSTRACT

This paper discusses different schemes of performance of passive solar heating of buildings. Based on the solution for heat conduction equation for active building constructions taking into account the influence of convective heat transfer and heat flux, incoming solar radiation, the ways of energy-saving facilities' operation is analyzed. It is shown that to increase the efficiency of such systems, an individual design should be performed taking into account the climatic features of the construction area, and the choice of rational combinatorics for outer shell, such as movable shielding heat-protective device, and creating an air gap between the accumulating and heat-insulating layers. Based on the calculations, the energy-active area of the bearing course of buildings, protected from the outer side with the translucent barrier is revealed. The suitable thickness of the accumulation layer for recycling process of solar radiation is determined. The presented innovative technical solutions could help to enhance the efficiency of solar energy utilization and contribute to a more active implementation of passive solar heating, expanding the scope of their territorial application.

KEYWORDS
energy saving, solar radiation, thermal energy, passive solar heating, thermal regime of outer shells

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Introduction

In the past four decades, energy demand has risen in a broadly linear fashion along with the gross domestic product. Since 1971, each 1% increase in global GDP has been accompanied by a 0.6% increase in primary energy consumption, resulting in an annual increasing rate of energy demand at about 2.0 % (Dimitriev, 2013; International Energy Agency, 2004). At the same time, there are severe signals indicating that the energy consumption strategy should be strongly modified in the near future. One signal comes from the fact that the organic fuel supplies (particularly oil and gas) are exhausted and will come to the end in a few tens of years, and even the coal reserves will run out faster than

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many believe (Heinberg & Fridley, 2010; Shafiee & Topal, 2009). The second signal comes from the fact that the global climate is now sensitive to the increasing level of energy consumption and carbon dioxide production as a result of such kind of activity, respectively. In this respect, renewable sources of energy, such as sun, wind, tides, etc., attract more and more attention. One of scenarios relies on the renewable hydrogen economy, where hydrogen, as the major energy carrier, can be produced through solar irradiation of water and causes no pollution except water (Crabtree, Dresselhaus, & Buchanan, 2004; Marbán & Valdés-Solís, 2007).The other ways concern artificial methods of solar energy conversion into various forms convenient for a subsequent storage and use of this energy on demand. The artificial methods are traditionally divided into the three major groups according to physical principles used for energy conversion and storage (Xu, Wang, & Li, 2014). The first method concerns a common property of matter to experience bulk heating where the value of the stored energy is proportional to specific heat capacity of the material used, giving rise to the so-called sensible heat (Faninger, n.d.; Kuravi, Trahan, Goswami, Rahman, & Stefanakos, 2013). The second method uses the property of the matter to absorb/release heat (so-called latent heat) upon phase transitions (Abhat, 1983; Sharma, Tyagi, Chen, & Buddhi, 2009; Zhou, Zhao, & Tian, 2012). If a certain phase transition takes place during which heat is absorbed, the reverse change will release the same amount of heat, so the energy can be stored as long as a certain phase of matter is sustained. The third method is chemical reactions during which energy is spent to create chemical compounds with high-energy chemical bonds which then release their energy upon disruption (Garg, Mullick, & Bhargava, 1985; N'Tsoukpoe, Liu, Le Pierrès, & Luo, 2009). Nevertheless, the renewable energy technologies are not yet cost competitive with the traditional, nonrenewable, fossil energy technologies.

Switching from the traditional energy sources to the modern ones, such as solar power, is not only capable of significantly saving money, but also has a positive impact on the environment (Abhat, 1983; Imashev et al., 2016). In contrast to the developed countries, such as the USA or Germany, in the developing countries solar energy is not widely used. This is due to the lack of the necessary technological level (Dimitriev, 2013). However, the growth of energy demand leads to the search for new energy sources.

One of the options to soften the energy demands is the development of passive solar construction design. In passive solar construction design, windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. This is called passive solar design because, unlike active solar heating systems, it does not involve the use of mechanical and electrical devices (Doerr, 2012). Therefore, the passive solar heating can be considered as a rather cheap alternative to the other energy technologies.

The key to design a passive solar building is to best take advantage of the local climate performing an accurate site analysis. For example, highly optimized systems of the passive solar heating allows one to dramatically reduce the estimated 40% of energy consumed in the average Australian home (Department of the Environment, Water, 2008) and more than 75% in the southwest United States (New Mexico Solar Association, n.d.) for space heating and cooling. Elements to be considered include window placement and size, and glazing type, thermal insulation, thermal mass, and shading (Norton, 2014). Passive solar design techniques can be applied most easily to new buildings, but existing buildings can also be adapted or modified.

Despite the accessibility and simple execution of passive solar heating devices, their operation may be accompanied by unreasonably high losses of useful heat or excessive overheating in the summer months. The expected efficiency increase of such systems for solar radiation utilization will be possible if the design of the structural elements is based on mathematical modeling and the application of the shielding devices of various modifications. In this paper, the ways of energy-saving operation of facilities are examined based on the solution of heat conduction equation for active building constructions taking into account the influence of convective heat transfer and heat flux, coming from solar radiation. It is shown that to increase the efficiency of such systems, an individual design should be performed taking into account the climatic features of the construction area, and choice of rational combinatorics of external enclosure, such as movable shielding heat-protective device, creating an air gap between the accumulating and heat-insulating layers, etc.

Purpose of the study

The aim of this study is to increase the efficiency of passive solar heating.

Research questions

What are the benefits of using passive solar heating?

Methods

For the rational construction of the face-integrated solar heating systems, the main issue is the distribution of the thermal regime generated in absorbing and accumulating layer. To study the temperature field arising in energy-active building constructions, we use the heat conduction equation of the plate in the following form

$$\frac{\partial \theta}{\partial \tau} = a\frac{\partial^2 \theta}{\partial x^2}, \tag{1}$$

where θ – the environment temperature in a certain point of space and time (oC); τ – time (s); a – temperature conductivity coefficient (m²/s).

Under given conditions of heat transfer, the origin of coordinates is advisable to place on the surface (Figure 1) exposed to solar radiation. In this case, the boundary conditions can be written as

when $x = 0$, $$-\lambda\frac{\partial \theta}{\partial x}\bigg|_{x=0} = q_S - \alpha_1\theta_{x=0}; \tag{2}$$

when $x = \delta$, $$-\lambda\frac{\partial \theta}{\partial x}\bigg|_{x=\delta} = \alpha_2\theta_{x=\delta}; \tag{3}$$

where λ – coefficient of thermal conductivity of the wall material, W/(m·oC); δ – thickness of wall (m); qS is the capacity of solar radiation received per area unit of the construction through the glass shell, W/m²; α_1, α_2 – heat transfer coefficients, W/(m²·oC).

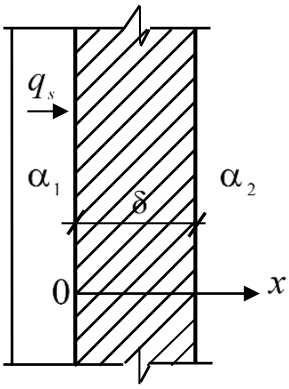

Figure 1. Scheme of heat transfer in passive solar heating.

The calculations are carried out for conditions of the middle latitudes (~50 °N), which is a large part of the territory of Europe, Russia and North America.

Data, Analysis, and Results

Calculation of the temperature distribution in the storage layer

It should be noted that the most reliable results of the analytical solutions of the heat equation can be obtained for tasks of semibounded arrays of different homogeneous materials (Rizzi, van Eck, & Frey, 2014). As it was shown in works (Tyagi, Ranjan, & Kishore, 2014), numerical simulation of temperature regimes of the absorbing accumulating layer requires a thorough analysis of design values database to identify parameters that have a major influence on the studied process. Therefore, we propose to represent the solution of equation (1) in the form of correspondence, which models periodic changes in the present thermal conditions the most adequately

$$\theta = e^{kx}\left[A_1\cos(\omega\tau + kx) + A_2\sin(\omega\tau + kx)\right] + e^{-kx}\left[A_3\cos(\omega\tau - kx) + A_4\sin(\omega\tau - kx)\right] \tag{4}$$

The first member on the right side of expression (4) is determined by energy radiation into the environment by the building construction as it is heated by solar radiation; the second one is recorded on the basis of absorption of the heat flux to the external surface of the construction and transmission of it into an array by conduction.

We define a constant k by differentiating the equation (4) in terms of the variables τ and x in accordance with (1),

$$\frac{\partial\theta}{\partial\tau} = \omega e^{kx}\left[-A_1\sin(\omega\tau + kx) + A_2\cos(\omega\tau + kx)\right] + \omega e^{-kx}\left[-A_3\sin(\omega\tau - kx) + A_4\cos(\omega\tau - kx)\right], \tag{5}$$

$$\frac{\partial\theta}{\partial x} = ke^{kx}\left[(A_1 + A_2)\cos(\omega\tau + kx) + (A_2 - A_1)\sin(\omega\tau + kx)\right] + ke^{-kx}\left[-(A_3 + A_4)\cos(\omega\tau - kx) + (A_3 - A_4)\sin(\omega\tau - kx)\right], \tag{6}$$

$$\frac{\partial^2\theta}{\partial x^2} = k^2 e^{kx}\left[2A_2\cos(\omega\tau + kx) - 2A_1\sin(\omega\tau + kx)\right] + k^2 e^{-kx}\left[2A_4\cos(\omega\tau - kx) - 2A_3\sin(\omega\tau - kx)\right] \quad (7)$$

Substituting (5) and (7) in the differential equation (1) we get

$$k = \sqrt{\frac{\omega}{2a}}, \quad (8)$$

where $\omega = 2\pi/z$ – oscillation frequency; z is the period of oscillation.

To determine the constants in the correspondence (4), we use boundary conditions (2) and (3). As the equation (2) contains the heat flow transferred to the surface of the shell, which is used in passive solar heating, then we will use the function of the form (Ministry of Regional Development of Russia, 2012) for its approximation

$$q_S = C\cos\omega\tau + D\sin\omega\tau \quad (9)$$

Then from boundary conditions (2) will receive

$$-\lambda k\left[\cos\omega\tau\left(A_1 + A_2 - A_3 - A_4\right) + \sin\omega\tau\left(A_2 - A_1 + A_3 - A_4\right)\right] = \\ = \cos\omega\tau\left(C - \alpha_1\left(A_1 + A_3\right)\right) + \sin\omega\tau\left(D - \alpha_1\left(A_2 + A_4\right)\right) \quad (10)$$

Subtract the right side from the left side of equation (10)

$$\cos\omega\tau\left[-C + \alpha_1\left(A_1 + A_3\right) - \lambda k\left(A_1 + A_2 - A_3 - A_4\right)\right] + \\ + \sin\omega\tau\left[-D + \alpha_1\left(A_2 + A_4\right) - \lambda k\left(A_2 - A_1 + A_3 - A_4\right)\right] = 0 \quad (11)$$

Analyzing the expression (11), we can conclude that, since the functions $\cos\varpi\tau$ and $\sin\varpi\tau$ are linearly independent, the equation (11) has a solution if

$$A_1\left(\alpha_1 - \lambda k\right) + A_2\left(-\lambda k\right) + A_3\left(\alpha_1 + \lambda k\right) + A_4\left(\lambda k\right) = C, \quad (12)$$

$$A_1\left(\lambda k\right) + A_2\left(\alpha_1 - \lambda k\right) + A_3\left(-\lambda k\right) + A_4\left(\alpha_1 + \lambda k\right) = D \quad (13)$$

When using boundary condition (3) we will receive

$$-\lambda k e^{k\delta}\left[\left(A_1 + A_2\right)\cos(\omega\tau + k\delta) + \left(A_2 - A_1\right)\sin(\omega\tau + k\delta)\right] + \lambda k e^{-k\delta}\left[\left(A_3 + A_4\right)\cos(\omega\tau - k\delta)\right] - \\ -\lambda k e^{-k\delta}\left[\left(A_3 - A_4\right)\sin(\omega\tau - k\delta)\right] = \alpha_2 e^{k\delta}\left[A_1\cos(\omega\tau + k\delta) + A_2\sin(\omega\tau + k\delta)\right] + \\ + \alpha_2 e^{-k\delta}\left[A_3\cos(\omega\tau - k\delta) + A_4\sin(\omega\tau - k\delta)\right] \quad (14)$$

The equation (14) has a solution, respectively, when

$$A_1\left[e^{k\delta}\left(\left(\alpha_2 + \lambda k\right)\cos k\delta - \lambda k\sin k\delta\right)\right] + A_2\left[e^{k\delta}\left(\lambda k\cos k\delta + \left(\alpha_2 + \lambda k\right)\sin k\delta\right)\right] + \\ + A_3\left[e^{-k\delta}\left(\left(\alpha_2 - \lambda k\right)\cos k\delta - \lambda k\sin k\delta\right)\right] + A_4\left[e^{-k\delta}\left(-\lambda k\cos k\delta + \left(\alpha_2 - \lambda k\right)\sin k\delta\right)\right] = 0 \quad (15)$$

$$A_1\left[e^{k\delta}\left(-\left(\alpha_2 + \lambda k\right)\sin k\delta - \lambda k\cos k\delta\right)\right] + A_2\left[e^{k\delta}\left(-\lambda k\sin k\delta + \left(\alpha_2 + \lambda k\right)\cos k\delta\right)\right] + \\ A_3\left[e^{-k\delta}\left(\left(\alpha_2 - \lambda k\right)\sin k\delta + \lambda k\cos k\delta\right)\right] + A_4\left[e^{-k\delta}\left(-\lambda k\sin k\delta + \left(\alpha_2 - \lambda k\right)\cos k\delta\right)\right] = 0 \quad (16)$$

Thus, we obtain a system of linear equations (12, 13, 15, 16), from which we can determine the coefficients A_1, A_2, A_3, A_4, included in the function (4).

For this reason, we consider a passive heating carried out using the south outer wall made of sand-lime brick and having the translucent coating from the outer side (Figure 1 and 2). The fencing material has the following properties: coefficient of thermal conductivity 0.76 W/(m·oC), specific heat 0.88 kJ/(kg·°C) and a density 1800 kg/m^3. Calculations are going to be performed for four design options for the wall, where its thickness corresponds to the following sizes: 120, 250, 380 and 510 mm. The coefficients of heat transfer from the outside and the inside of the fence will be taken in accordance with (Shchukina, Chudinov, & Kuznetsova, 2006) equal to 12 and 8.73 W/(m^2·oC).

Figure 2. Reinforced concrete load-bearing constructions of the building under the translucent decorative cover.

Heat flow, transferred in March through the glazing to the surface of the vertical fence, can be used for areas of 50°N with sufficient accuracy of the correspondence (Ministry of Regional Development of Russia, 2012)

$$q_S = -84\cos\omega\tau - 56{,}84\sin\omega\tau \tag{17}$$

Then solving the system of linear equations (12, 13, 15, 16) for the given conditions using the Cramer formulas, we will get the correspondences:

when δ = 120 mm

$$\theta = e^{8,71x}\left[0{,}0656\cos(\omega\tau + 8{,}71x) + 0{,}2715\sin(\omega\tau + 8{,}71x)\right] + \\ + e^{-8,71x}\left[-2{,}9409\cos(\omega\tau - 8{,}71x) - 4{,}2032\sin(\omega\tau - 8{,}71x)\right]; \tag{18}$$

when δ = 250 mm

$$\theta = e^{8,71x}\left[-0{,}0049\cos(\omega\tau + 8{,}71x) - 0{,}027\sin(\omega\tau + 8{,}71x)\right] + \\ + e^{-8,71x}\left[-3{,}0532\cos(\omega\tau - 8{,}71x) - 4{,}1285\sin(\omega\tau - 8{,}71x)\right]; \tag{19}$$

when $\delta = 380$ mm

$$\theta = e^{8,71x}\left[-0,0025\cos(\omega\tau + 8,71x) + 0,00068\sin(\omega\tau + 8,71x)\right] + $$
$$+ e^{-8,71x}\left[-3,0421\cos(\omega\tau - 8,71x) - 4,1338\sin(\omega\tau - 8,71x)\right]; \qquad (20)$$

when $\delta = 510$ mm

$$\theta = e^{8,71x}\left[0,00014\cos(\omega\tau + 8,71x) - 0,00026\sin(\omega\tau + 8,71x)\right] + $$
$$+ e^{-8,71x}\left[-3,0429\cos(\omega\tau - 8,71x) - 4,1347\sin(\omega\tau - 8,71x)\right]; \qquad (21)$$

As it can be seen from equations (18-21), with increasing thickness of the material layer, its radiation to the environment greatly reduces, which is described by the first member of the equation, therefore, this component can then be neglected.

The graph of temperature change (Figure 3) at 3 PM, built according to the equation (21) for the wall of sand-lime brick for the building, located near 50 °N., shows that intense temperature damping takes place in the fences with thickness up to 250 mm. At the same time, at the thickness of 380 mm or more, the impact of these changes on the indoor microclimate is significantly reduced during the day. Therefore, if the air environment of the premises should be warmed in a short time, then it is expedient to use less massive building constructions for passive solar heating, using them mostly for buildings of public and industrial purposes, with single-shift operation mode. In other cases, the thickness of the fence should not be significantly increased, but it is necessary to set the heat shielding devices, which regulate the solar radiation flow between glazing and supporting construction (Shchukina et al., 2006).

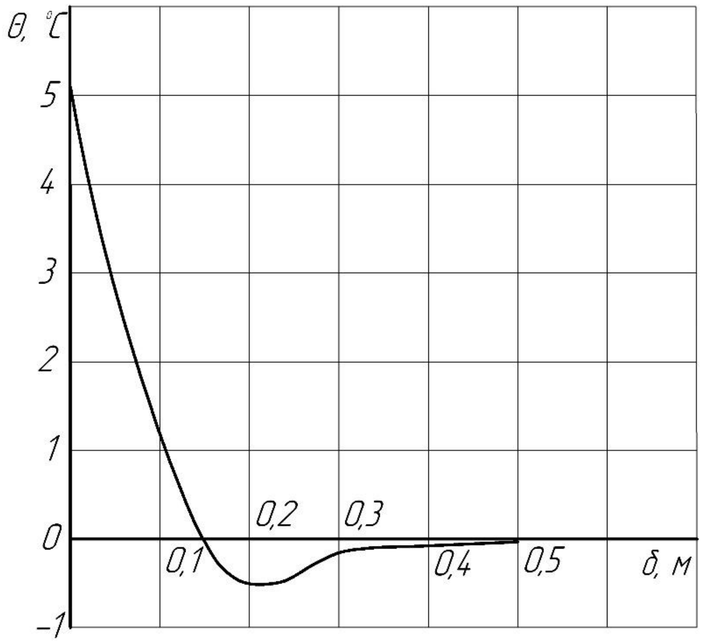

Figure 3. Change of relative temperature in the thickness of the fence.

Two-in-one: combination of accumulating and insulating layer

Taking into account the difficult weather conditions of winter seasons in most of the middle latitudes, particularly in Russia, construction of fencing and utilizing of the solar radiation should have not only the storage layer, but also the high heat-protective properties. An appropriate technical solution is proposed in the patent ("A positive decision on the application for a discovery № 2015106253 of 24.02.2015. Solar Thermal Collector," n.d.), offering bearing accumulative layer, closed from external influence by translucent enclosure, and having an effective thermal insulation with organized air gap.

The diagram of external wall ("A positive decision on the application for a discovery № 2015106253 of 24.02.2015. Solar Thermal Collector," n.d.) at its southern orientation shown in Figure 4, allows organizing heat removal from the storage material that is heated by solar energy during the cold period of the year by opening the air valves. The temperature of the air entering through the lower air valves is enhanced by contact with the irradiated surface, and then the warm air is directed into the heated room through the upper valves. With closed air valves, a layer of thermal insulation creates thermal resistance, significantly reducing heat loss during the heating season and heat input during the summer period. For the efficient utilization of solar radiation, the automatic switching of valves should be provided, using the electricity produced by a small number of solar cells, located on the solar-active face of the building. In addition, it is advisable to install the cooling system of the storage layer for the warm period of the year, which, carrying the excess heat removal, will direct the heated heat conductor on the hot water supply. It can be performed through a batch of tubes on the absorbing surface of the storage layer (Figure 5), which should be coated with a paint material with a high coefficient of thermal conductivity. When designing such cooling system, the photoconverters should be placed on the pipes, thereby preventing their overheating, which reduces the production of power.

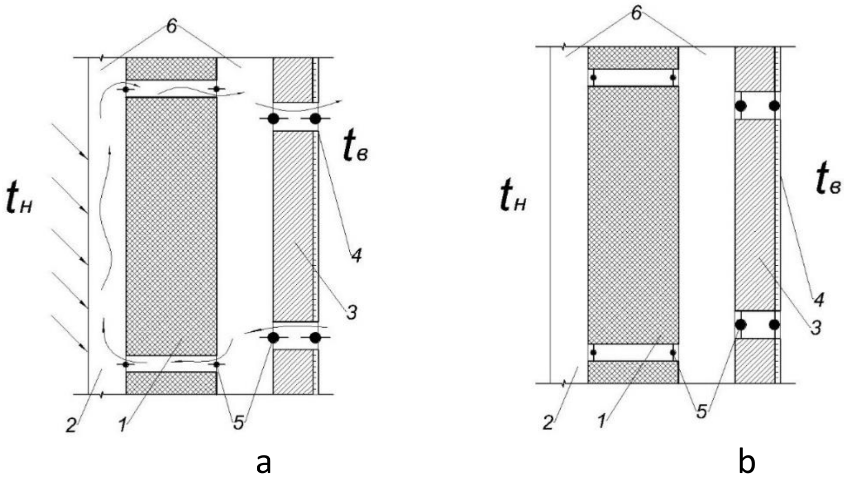

Figure 4. Diagram of passive solar energy utilization at energy-active outer fence: a — under intensive irradiation in the cold period of year; b — at night, or under adverse weather conditions during the heating period, or during the summer months; 1 — heat storage bearing layer of the enclosing construction; 2 — translucent cover; 3 — heat insulating material; 4 — interior furnishing; 5 — valves; 6 — air gap.

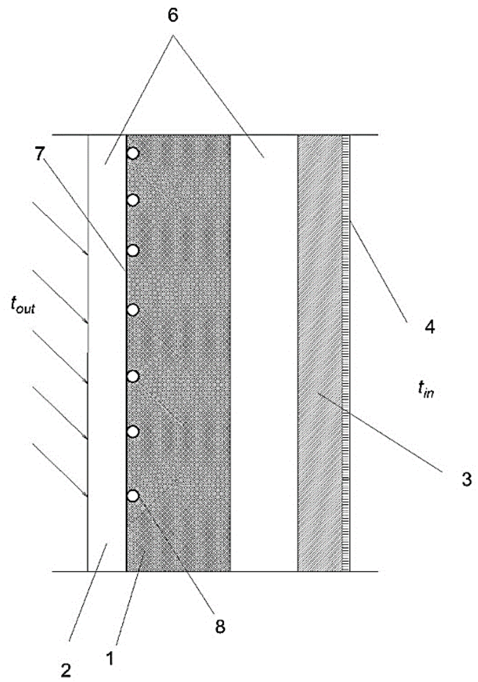

Figure 5. Top view of the energy-active outer fencing cut: 1-6 — the same as in Figure 4; 7 — dark paint coating with a high coefficient of thermal conductivity; 8 — pipes with the heat conductor.

When designing outdoor enclosures with the function of solar radiation utilization, the thickness of the applied thermal insulation can be determined by thermal calculation under the condition of energy saving. For a rough estimation of the required volume of the storage material, we use the heat balance equation, neglecting the convection heat transfer in the air gap that corresponds to the closed valves mode. This mode at the initial stage of solar radiation absorption by the south face allows heating the accumulating layer with a temperature higher than in internal premises. This condition will provide further passive solar heating.

Considering the adopted assumption, the amount of heat in MJ/(m²·day), absorbed by the irradiated surface of external fence under the translucent coating with its area of 1 m², can be determined from the expression (Marbán & Valdés-Solís, 2007)

$$q_{\mathrm{K}} = \overline{E}_{\mathrm{OP}} \Phi \eta_0 , \tag{22}$$

where $\overline{E}_{\mathrm{OP}}$ — average daily amount of total solar radiation transferred to a vertical surface considering its orientation during the reporting month, MJ/(m²·day); Φ is the degree of solar radiation, depending on the design features of collectors and tending to one for the most efficient devices of direct conversion of solar energy; η_0 is the effective optical efficiency of the collector of passive utilization system.

Absorbed radiation will contribute to heating of the storage layer in accordance with the correspondence

$$q_{\mathrm{K}} = c \cdot m \left(t_{\mathrm{K}} - t_{\mathrm{H}} \right), \tag{23}$$

where c – the specific heat capacity of the storage material J/(kg·°C); m – mass of the heated material, kg; t_H, t_K – initial and final temperature of the storage layer, °C.

With the help of the irradiated layer thickness, with the size of its perceiving surface of 1 m², from equations (22, 23), we can find a finite temperature of mean monthly actinometrical parameters and the outdoor air temperature

$$t_{\mathrm{K}} = t_{\mathrm{H}} + \frac{\overline{E}_{\mathrm{OP}} \Phi \eta_0}{\delta \rho c}, \tag{24}$$

where δ — the thickness of the accumulating reinforced-concrete layer, m; ρ — material density, kg/m³.

Discussion and Conclusion

The feature of Russia is the relatively low price of energy, availability of the connection to the gas network, coverage of all inhabited areas with electricity supply systems, which leads to lack of an enabling framework for the dissemination of alternative energy sources in Russia (Dimitriev, 2013). Therefore, based on the current situation, it is necessary to use the sun's energy not in the active energy converters, but in passive heating systems.

Let us consider the achieved temperature in the reinforced-concrete bearing layer of the outer fence of the southern orientation at the passive utilization of solar radiation on the example of the climatic conditions of the Moscow region (55 N°). Figure 6 demonstrates the calculations results that show the need for a storage construction use, the thickness of which shall not be more than 70 mm and not less than 50 mm in average efficiency not exceeding a value of 0.4 for this type of solar collectors. To improve the efficiency of passive solar heating, it is necessary to use glazing with a high conductivity rate and paint coatings, enhancing the adsorption effect and the thermal conductivity of the radiation-perceiving surface of accumulative layer. Then with projected increase in efficiency to value of 0.5, bearing layer of reinforced concrete should be designed with a thickness of 70 mm to 100 mm, which in accordance with the theory of the thermal regime will provide its good warming for solar energy utilization. If we anticipate a small thickness of the construction, then the achieved high temperature in the layer allows placing the water cooling system on the absorbing surface ("A positive decision on the application for a discovery № 2015106253 of 24.02.2015. Solar Thermal Collector," n.d.), and at sufficient irradiance, the heat conductor can be directed to hot water supply.

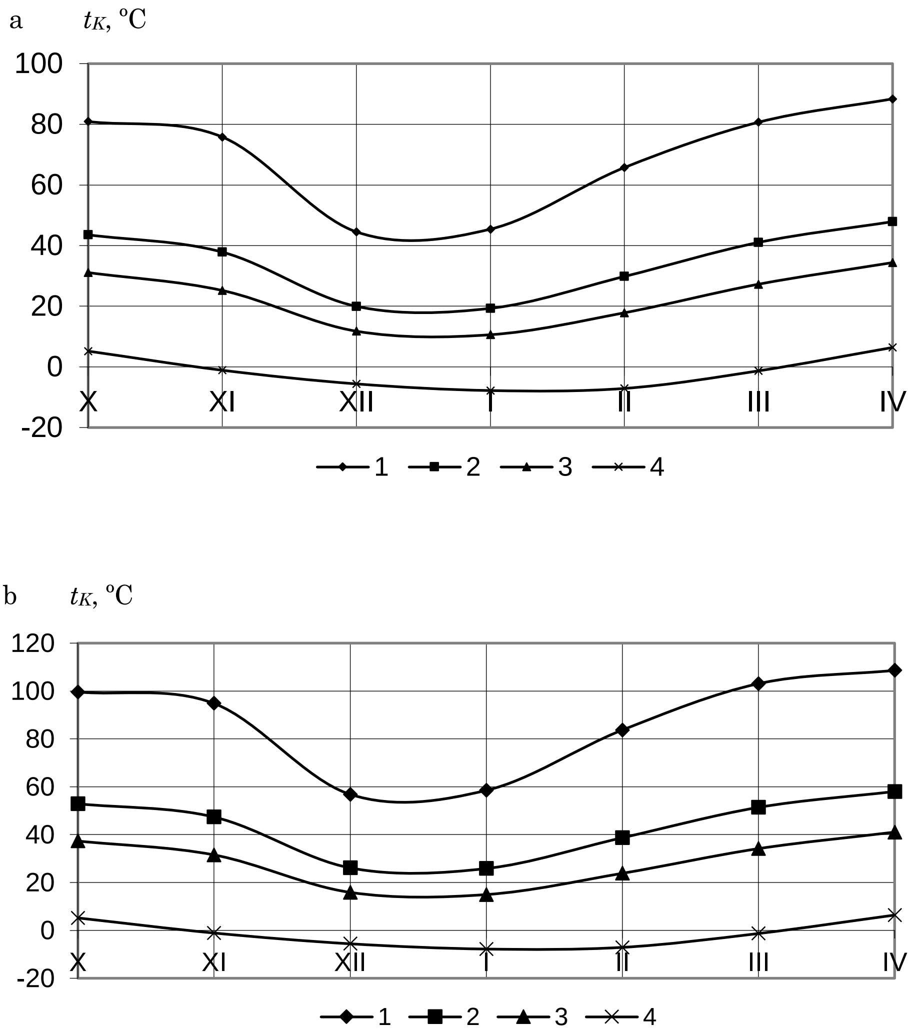

Figure 6. Achieved temperature of the accumulating reinforced-concrete layer at its different thickness during the heating period depending on the month under the influence of solar radiation: a — at the efficiency of passive systems, which is equal to 0.4; b — taking into account further increase of optical performance and achievement of efficiency values of 0.5; Curves 1, 2, 3 — heating temperature of the layer when its thickness is 50, 100, 150 mm, respectively; curve 4 — average monthly outer air temperature.

Implications and Recommendations

On the basis of theoretical research, we developed recommendations for creation of optimal regimes of passive solar heating operation. It is shown that the optimal conditions are achieved as a result of the combination and structural performances of the storage material, shielding devices, and thermal protection, which prevents heat loss and excess heat input, respectively. A distinctive feature of the developed model from previously proposed models of thermal regimes is a more precise definition of the energy-active layer thickness in storage material for designing a new generation constructions. In particular, on the basis of the obtained results, we can anticipate that in the outdoor design of energy-efficient buildings' walls for the southern regions, corresponding to 40 oN, the thickness of the accumulation layer should not exceed 200 mm. Moreover, for buildings located to the North, with each subsequent degree you need to reduce the accumulation layer thickness for 6-7 mm. The thickness of thermal insulation is appropriate to calculate in accordance with the regulatory calculation from the energy conservation condition for the project area. The reliability of the obtained results is confirmed by good convergence in the harmonic oscillations description, which are characteristic for periodic impact of solar radiation on the fence surface.

The paper also describes the prospectivity of the additional air layer application between the bearing layer and the insulating material, which contribute to greater convective heating of the air entering subsequently to a heated room. On the other hand, the use of new, inexpensive, easy-to-maintain and moveable shielding heat-protective constructions for translucent enclosures will help to ensure not only the control and regulation of heat input from solar radiation in summer period, but also their efficient use in the cold season. This will ultimately increase the efficiency of passive systems and ensure their wider spatial distribution.

Experience in the construction and maintenance of energy efficient buildings with face-integrated systems in Europe, North America and Australia is already showing a good result in the utilization of solar energy. We believe that in the future, the creation of the intellectual management mode of the solar energy reception and its optimal distribution depending on the specific operating conditions of the building will be one of the main research directions in the field of passive solar heating.

Disclosure statement

No potential conflict of interest was reported by the authors.

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