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Constructive Solutions of Energy-Active Fences for Solar Radiation Utilization and Methodological Arguments for Their Economic Efficiency

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Abstract. The design of an external wall is proposed, it allows for efficient utilization of solar energy to reduce the load on buildings heating. A special feature of the technical solution is the location of thermal insulation from the inside of the energy-active fence with air space formation relative to the accumulating layer. The given design makes it possible to avoid accommodations overcooling in case of adverse weather conditions during the cold season and overheating during warm weather. It was proposed to base costs increase for energy-saving buildings construction including those with integrated solar radiation conversion systems and to use the methodology for estimating additional technical solutions based on the calculation of economic efficiency.

The most widespread and affordable renewable source in the whole territory of the Russian Federation is solar radiation, that has been successfully utilized for heating, hot water supply and power supply in Europe and North America for decades. Such an active nontraditional resources replenishment, firstly, is associated with desire for energy independence and stimulating programs of state support. However positive European experience is often not applicable to the Russian Federation harsh climatic conditions.

Hot summer months and extremely low outdoor temperatures during the winter season dictate special requirements for fencing structures, thermal protection and energy saving in life-saving buildings system.

Despite the difficult meteorological conditions, the achieved results during mass exploitation of solar power plants in North America show the potential of their use on the territory of Russia.

A significant part of the thermal energy consumed by the buildings is lost during the cold period of the year through external fences. But their irradiation during a sufficient number of hours of sunshine and technical solutions aimed at effective absorption of long-wave radiation, reduces consumption of thermal energy by heating systems.

Therefore, in climatic regions with sufficient resource availability of solar radiation, it should be passively utilized for energy saving maintenance of accommodations microclimate parameters [1].

Complex climatic conditions, especially the winter seasons in the greater territory of the Russian Federation, for outdoor fences that utilize solar radiation, require not only the presence of an
accumulating layer, but also the compliance with high heat-shielding properties. Such a combination is achieved with technical solution [2] using a load-bearing accumulation layer, that is covered from external exposure with a translucent enclosure, and additionally has an effective thermal insulation with an organized air layer. Realization of this principle of construction will not cause difficulties with the current trends in buildings architecture. Projected large areas of glazing should be used for the organization of energy-active external fences on buildings southern facades.

The scheme of the outer wall with southern orientation shown in Figure 1 [2], allows to organize a heat sink from accumulating material heated by solar energy during the cold period of the year by means of air valves opening. At the same time, the temperature of the air entering through the lower air valves rises during contact with irradiated surface, then through the upper valves, warm air is directed to the heated room. In case of closed air valves, the thermal insulation layer creates thermal resistance, significantly reducing heat loss during cold periods and heat input during warm ones. For effective solar radiation disposal, valves automatic switching should be provided for this purpose it is necessary to use electricity generated by a small number of photocells located on the helioactive facade of a building. Overheating of the accumulating layer during summer season can be avoided by providing translucent enclosure rotary blinds or a cooling system with tubes placed on the radiation absorbing surface and performing the function of a solar thermal collector for consumers hot water supply.

Figure 1. Scheme of solar energy passive utilization with energy-efficient external fencing: A - with intensive irradiation during the cold season; B - at night or during adverse weather conditions during the cold period, or in summer months; 1 - heat-accumulating layer; 2 - translucent enclosure; 3 - heat-insulating material; 4 - interior onlay; 5 - valves; 6 - air layer.

There are various designs of energy-active external fences for buildings passive solar heating [1, 3]. To utilize solar radiation, translucent heat-insulating panels are mounted on buildings southern facades with the formation of air layers in load-bearing building structures. The air falling into the interlayer is heated under the influence of solar radiation and, if necessary, is directed to ventilation emissions heat recovery ventilation, and then to an accommodation. So-called solar ventilation towers are also used and are installed in the form of mines on the outside of exterior walls. The surface of mines can be made with perforated or finned metal plates with paint coating that have a high absorbing capacity.

One of the latest concepts of energy-efficient buildings construction is creation of external fences made with thermally active moving functional layers, some of which can contain accumulating materials that undergo changes in the aggregate state. Opening and closing of energy-active layers occurs automatically and in accordance with a specified control program that takes into account time of day and weather conditions. It is difficult to assess payback and the subsequent energy-saving effect
during use of such complex systems of passive heating, as costs construction can greatly exceed consumption of traditional resources economy.

During energy-active external fence construction, the thickness of the thermal insulation applied must be determined in accordance with the conditions for observing energy-saving thermal regimes [4]. For an approximate estimate of the required volume of the accumulating material, we use the heat balance equation, neglecting the convective heat exchange in the air layer that corresponds to the closed valves regime. This mode at the initial stage of solar radiation absorption by the southern facade allows the accumulating layer to warm up with the temperature of the indoor air in excess, which in the future will provide a mode of passive solar heating.

Taking into account the accepted assumption, the amount of heat, in J / (m² day), absorbed under the translucent enclosure of the irradiated surface of the outer fence with its area of 1m², can be determined from the expression [5]:

\[ q_C = \overline{E_{or}} \Phi \eta_0 \]  

where \( \overline{E_{or}} \) — average daily amount of total solar radiation entering the vertical surface taking into account its orientation for the month in question, J / (m² · day) \( \Phi \) is the degree of solar radiation use, depending on collectors structural features [4] and tends to unity with simple devices for solar energy direct conversion; \( \eta_0 \) — effective optical efficiency of the passive recycling system collector. The absorbed radiation will promote the heating of the accumulating layer in accordance with the dependence:

\[ q_C = cm(t_{in} - t_F) \]  

where \( C \) - the specific heat of the accumulating material, J / (kg · °C); M is the mass of the heated material, kg; \( T_{IN}, t_F \) - initial and final temperature of the accumulating layer, °C.

Specifying thickness of the irradiated layer, with the size of its perceiving surface 1000x1000 mm from the equations (1, 2), we can find out the final temperature at the average monthly actinometric parameters and outside air temperature:

\[ t_F = t_{in} + \frac{\overline{E_{or}} \Phi \eta_0}{\delta \rho C} \]  

where \( \delta \) — thickness of accumulating reinforced concrete layer, m; \( \rho \) - density of material, kg / m³.

Consider, for example, the climatic conditions of the Moscow Region [5] the achieved temperature indexes in the reinforced concrete bearing layer of the outer fencing of the southern orientation with passive disposal of solar radiation. The results shown at Fig. 2 demonstrate the need for a light reinforced concrete structure, the thickness of which can be no more than 70 mm and not less than 50 mm with the current efficiency for this type of collectors not exceeding 0.4. During glazing using with high transmission coefficient and paint coatings for storage layer, maximizing the absorbing effect, the efficiency of passive disposal is increased. Then, within its predictable increase to 0.5, the supporting structure should be 100 to 70 mm thick. If the design solutions provide for an insignificant thickness of the reinforced concrete structure, it is advisable to place a water cooling system [2] on the irradiated surface, the coolant of which, with intensive irradiation, will be sent to consumers for hot water supply.

The presented calculation results (Figure 2) show the final temperature of the accumulating layer during the charging period. Often, to justify the proposed technical solutions, one should have a predictable change in thermal conditions during heating. Therefore, it is necessary to consider the heat balance equation during accumulating layer heating with allowance for losses in favor of the environment:

\[ cm \frac{dt}{d\tau} = I \eta_0 - K(t - t_0) \]
where \( \tau \) — time of charging of the accumulating layer with the report from the beginning of the light day, for which \( \tau = 0 \); \( I \) — flux density of solar radiation entering the surface of the energy-active fence, W / m\(^2\); K is the heat loss coefficient from the heated accumulating layer to the environment, W / (m\(^2\) °C); T\(_0\) is the ambient temperature of a layer, °C. In equation (4) we introduce the conventional irradiance coefficient of the enclosing surface, equal to:

\[
K_s = \frac{I}{(t - t_0)}
\]

Assuming a constant average value of the flux of solar radiation, that is typical for each hour of daylight, expression (4) can be written in the following form:

\[
\frac{cm}{d\tau} = (K_s - K) (t - t_o)
\]  (5)

Provided \( \tau = 0 \), storage layer temperature is equal to the initial \( t_{IN} \), and solution of (5) is the dependence

\[
t = t_0 + (t_{IN} - t_0) e^{\frac{(K_s - K)\tau}{mc}}
\]  (6)

![Figure 2](image)

**Figure 2.** The temperature of the accumulating reinforced concrete layer, reached under the influence of solar radiation, for various thicknesses: a - for modern efficiency of passive systems equal to 0.4; B - taking into account the further increase of optical indicators and the achievement of efficiency of 0.5; 1, 2, 3 - the heating temperature of the layer at its thickness of 50, 100, 150 mm, respectively; 4 - average monthly outside air temperature.

Calculations carried out according to the formula (6) (Figure 3) with an average flux density of solar radiation of 150 W/m\(^2\), an outdoor air temperature of 0 °C, an efficiency of 0.4 and reinforced concrete panel thickness - 100 mm indicate the need for insulating glass units with low heat transfer coefficient as a translucent enclosure for energy-active external structures.

To evaluate enclosing structures economic efficiency that contribute to solar energy utilization, it is suggested to use the difference in unit costs for external wall construction and the subsequent heating of 1m\(^2\) of the total building area according with typical approaches to construction and with structural solutions using solar radiation:

\[
E_p = E_{s,hb}^{upd} - E_{s,hb}^{w}
\]  (7)

where \( E_p \) - economic effect of constructive solutions of fences using that utilize solar energy, p./m\(^2\) per year; \( E_{s,hb}^{upd} \) and \( E_{s,hb}^{w} \) — specific costs for construction and subsequent heating of 1m\(^2\) of a building total area, in correspondingly with a typical enclosing structure and a solar energy recycling facility, p./m\(^2\). In turn, a unit costs value for considered options for fences construction structural solutions is calculated according to the scheme:

\[
E_{s,hb} = \mu \cdot \alpha_i^{pwd} \cdot E_{pd} + E_u
\]  (8)
where $E_{s,bb}$ - specific costs value of construction and subsequent heating of 1m² area, p./m²; $\mu$ - coefficient that takes into account a structure service life; $\alpha_{pi}^{nd}$ - norm of consumption of the enclosing structure for 1m² of the total area i-th constructional building system, m²/m²; $E_{pi}$ - construction costs of an enclosing structure, including materials and wall installation costs, p./m²; $E_{hE}$ - annual heating cost for 1 m² of total building area, p./m².

![Figure 3. Accumulating layer heating in charging mode: 1 - single glazing; 2 - single-compartment insulating glass unit](image)

It is necessary to indicate that factor value takes into account structure service life ($\mu$) is determined by degree of reliability and durability of constructed buildings. At the same time, the capital group is correlated with materials durability of non-replaceable structural elements (walls, frames, ceilings, foundations) with the greatest service life [6-8]. Depending on such structures service life, six groups of reliability and durability of buildings are distinguished: I - 126-150 years of service life; II - 101-125 years; III - 51-99 years; IV - 31-50 years; V - 16 - 30 years and VI - up to 15 years. Thus, knowing a building group, the coefficient can be determined by the formula:

$$\mu = \frac{1}{P_p}$$

where $P_p$ - a building service life, depending on the group, in years.

The obtained results convincingly prove the feasibility of passive solar heating systems designing according to architectural and planning trends, suggesting facade glazing. The proposed technical solution of the outer fence will allow not only to efficiently solar radiation dispose, but also to preserve the achieved temperature regime in accommodations due to thermal insulation use. To reduce heat loss to the environment and, accordingly, to increase the level of solar radiation utilization, it is necessary to protect the accumulating layer from external influence by means of insulating glass units. This will ensure the required thermal regime during its charging period and will reduce financial implications for heating under influence of weather conditions with a sufficient resource of external fences irradiation.

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