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EVALUATION OF ENERGY EFFICIENCY OF SOLAR ROOFING USING MATHEMATICAL AND EXPERIMENTAL RESEARCH

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Розроблено математичну модель роботи геліопокрівлі у системі теплопостачання. Теоретично отримано математичну залежність розрахунку температури нагріву теплоносія в баці-акумуляторі від інтенсивності теплового потоку та часу опромінення. Проведено планування повного факторного експерименту, описано процес проведення замірів та вимірювальну апаратуру, математичне оброблення отриманих результатів та представлення у вигляді графіків, номограм та аналітичних залежностей

Ключові слова: геліопокрівля, система теплопостачання, енергетична ефективність, геліосистема, сонячний колектор, сонячна енергія

Разработана математическая модель работы гелиокровли в системе теплоснабжения. Теоретически получена математическая зависимость расчета температуры нагрева теплоносителя в баке-аккумуляторе от интенсивности теплового потока и времени облучения. Проведено планирование полного факторного эксперимента, описан процесс проведения замеров и измерительная аппаратура, математическая обработка полученных результатов и представление в виде графиков, номограмм и аналитических зависимостей

Ключевые слова: гелиокровля, система теплоснабжения, энергетическая эффективность, гелиосистема, солнечный коллектор, солнечная энергия

1. Introduction

Of special importance today is the principle of energy efficiency and rational use of energy resources. At present, alternative energy has been widely used globally [1, 2]. One of the areas of alternative energy generation, which is based on direct application of solar radiation, is the solar energy, which is practically unlimited and is environmentally friendly [3].

The scientists estimate that the amount of solar energy received by the Earth exceeds annual energy consumption of the planet's population by 27 000 times. The annual flow of solar radiation per 1 m^2 of a horizontal surface in the southern regions of Ukraine is 1250–1350 kW/m^2, and the duration of solar radiation is approximately 2000 hours. In this regard, there arises a need for efficient use of solar energy, the easiest way to use it being its conversion to thermal energy [4].

2. Literature review and problem statement

At present, there are a large number of solar collectors, which differ in design and technical-economic indicators [5, 6]. The vast majority of solar collectors are fabricated in the form of flat structures, which results in unstable performance over daylight hours because of changes in the incident angles of sunrays [7]. Another significant shortcoming of these collectors is the high cost and complexity of manufacturing. In addition, high dimensions of the flat surface of the rectangular shape of solar collectors leads to difficulties in architectural and technological installation of the required quantity of heat accumulators of this class directly on the facilities. It creates in this case additional weight loading on the structures of buildings, which host solar collectors.

Given this, very promising are the engineering and technological solutions, which provide the possibility to combine structural and architectural features of separate elements of buildings and facilities [8].

One of the easiest ways to use solar heat given the existing roofs is the transmission of water or air through the surface of the roof [9]. However, conducted studies into such system revealed that a performance efficiency coefficient in this case is low, but insignificant costs related to converting an existing roof into a solar collector justify low performance efficiency coefficient.

There is also a solar profile [7], which is an elongated aluminum profile that has a thermal-sensitive surface, channels for liquid and air heat carrier and ribbing fastening with neighboring elements. However, effectiveness of such system is relatively small because of the low coefficient of capturing solar radiation over morning and evening hours.

There exist designed energy efficient protective structures in the form of roofs and outer walls of building facilities (residential, public, administrative, etc.), as well as the elements of surfaces of industrial objects (freezing, refrigeration and drying chambers, etc.). Such structures make it possible to effectively use solar radiation energy, as well as to utilize exhaust air heat for the needs of hot water supply, air conditioning and heat supply, and, if necessary, make it possible to implement the features of releasing excess heat and regulating heat accumulation [8]. Widely used Wall-mounted solar collectors are widely used, which serve simultaneously as protective structures [9].

The above technical solutions provide a possibility to create various architectural variants for installing a solar collector at the existing structures, as well as broad architectural options when designing new facilities. However, a number of disadvantages, including high cost, low efficiency of work during morning and evening hours, and complex design [10], characterize these systems.

Among the structural elements of buildings, of special are the surfaces of roofs made of corrugated metal sheets, which opens up possibilities for more effective capturing of solar radiation in the morning and evening hours. In this regard, it is important to develop a solar roofing that combines the functions of a solar collector and a metal corrugated part of a pitched roof. Such system could be used both in new buildings and on existing roofs and could be integrated into traditional combined systems of solar heat supply [8, 11].

3. Research goal and objectives

The goal of present study is to determine energy efficiency of solar roofing in the system of solar heat supply.

To accomplish the goal, the following tasks have been set:

– to develop a mathematical model of the work of solar roofing in the system of solar heat supply;

– to perform experimental study into the work of solar roofing in the system of solar heat supply for the purpose of determining its characteristics.

4. Theoretical and experimental study into solar roofing

A comprehensive solution to the issues of fixing solar collector directly to the elements of roof has broad prospects because in this case a possibility of replacing part of the roof with them can be implemented. This eliminates additional load on the carrying structures and in general reduces the cost of solar heat supply. The most acceptable for such variant of the heating system is the southern-oriented pitched parts of roofs of the buildings, which are covered with corrugated metal sheets. This opens up broad possibilities of their performing the functions of a receiver of solar energy, as well as the achievement of a high degree of thermal conductivity through a wall of the pipes, which are in direct contact with a metal roof. A combination of the metal coating of the roof with a solar collector presents this variant of solar heat supply as a solar roofing. It can be used as standalone and combined heating systems, similar to the classic flat solar collectors.

A role of heat absorber in a solar roofing is performed by metal roofing material of the roof of the building, in particular a standard profile-corrugated sheet. The advantage of the profile heat absorber in comparison with the classic flat solar collectors is an increase by 25 % in the working surface area and a larger capacity to accept heat in the morning and evening hours [11]. To maximize the absorption of heat from the radiation source, outer surface of the corrugated sheet was painted black.

The heat, received by a heat absorber, is transferred to a heat carrier that is circulated inside the pipes of the circulation contour (Fig. 1). Due to the temperature difference and, respectively, the difference in the densities of heat carrier in the area of the inlet and outlet branch pipes of solar roofing, there occurs a circulation of the heat carrier from a solar roofing to the tank-accumulator. In order to improve effectiveness of the work of a solar roofing, we used a layer of thermal insulation 4 made of polystyrene of thickness 50 mm and a ray-reflective screen 3. Due to the selected measures and a selective coating on the outer surface of the heat absorber, the conditions are created for maximum absorption and transfer of the solar radiation received by the roof to the heat carrier.

To assess the effectiveness of solar roofing, we compiled the energy balance of the system of solar heat supply with a solar roofing, and conducted analytical studies whose purpose is to determine thermal-accumulation properties of the solar roofing.

The roofing material of the building absorbs solar energy, and the heat from it by convection and radiation enters the environment. The resulting energy is lost through the side and lower parts of the solar roofing, and the remaining energy from the roofing material of the building is transferred to the heat carrier. The heated heat carrier is fed to a hot water tank-accumulator.

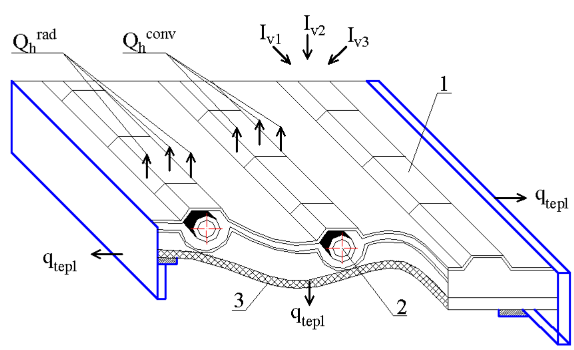

Fig. 1. Schematic of thermal balance of solar roofing: 1 — roofing material of the building; 2 — pipes of circulation contour; 3 — thermal insulation

To assess the work of solar roofing, the equation of thermal balance holds, which shows the useful energy and the losses:

$$\frac{Q_{ak}}{\Delta\tau} = Q_{son} - Q_h^{conv} - Q_h^{rad} - Q_{tepl} - Q_{b.a.} - Q_{tr}, \quad (1)$$

where Q_{ak} is the number of accumulated energy over time $\Delta\tau$, J; Q_{son} is the solar heat flow that arrives on a solar roofing, W;

Q_h^{conv}, Q_h^{rad}, Q_{tepl}, $Q_{b.a.}$, Q_{tr} are the heat losses, respectively, by convection, radiation, thermal conductivity, from the tank-accumulator and pipelines, W.

The amount of energy accumulated by the tank- accumulator, J:

$$Q_{ak} = c \cdot m \cdot \left(t_k - t_p\right), \quad (2)$$

where c is the specific heat capacity of heat carrier, J/(kg·K); m is the mass of heat carrier, kg; t_k and t_p are, respectively, the resulting and initial temperature of heat carrier, K.

The intensity of solar radiation I_v, W/m^2, which arrives to the corrugated solar roofing, is the sum of direct and scattered solar radiation during a day:

$$I_v = \int \left(G_b \cdot \cos\theta + Gd\right) dt, \quad (3)$$

where G_b, G_d are, respectively, the amount of direct and scattered solar radiation, J/m^2; θ is the angle between a direction of the flow of radiation and a normal to the surface of heat absorber, deg.

Solar thermal flow that arrives on a solar roofing is the result of absorption of heat by horizontal and respective pitched faces of the corrugated roofing sheet, W:

$$q_{son} = h \cdot \begin{pmatrix} F_i \cdot \int \left(G_{b1} \cdot \cos\theta + G_{d1}\right) dt + \int \left(G_{b2} \cdot \cos\theta + G_{d2}\right) dt + \\ + \int \left(G_{b2} \cdot \cos\theta + G_{d2}\right) dt \end{pmatrix}, \quad (4)$$

where h is the coefficient of absorption of solar energy by roofing material of the building; F_i is the area of absorption of the respective edge of the corrugated roofing material of the building, m^2.

Convective heat losses from the surface of the roofing material, W:

$$Q_h^{konv} = \alpha_h \cdot F_{tp} \cdot \left(t_{tp} - t_{n.}\right), \quad (5)$$

where α_h is the coefficient of heat transfer from the roofing material of the building to the environment, W/(m^2·K); F_{tp} is the heat absorber area, m^2; t_{tp} is the temperature of heat absorber, K; $t_{n.}$ is the ambient temperature, K.

Losses of heat by the radiation from the surface of the roofing material of the building to the environment, W:

$$Q_h^{rad} = \varepsilon_p^{tp} \cdot c_0 \cdot F_{tp} \left[\left(\frac{T_{tp}}{100}\right)^4 - \left(\frac{T_N}{100}\right)^4\right], \quad (6)$$

where ε_p^{tp} is the reduced relative coefficient of thermal radiation of roofing material of the building; c_0 is the emissivity of an absolutely black body, W(m^2·K^4); T_N is the temperature of sky, K.

Heat losses through the side and lower parts of the solar roofing, W:

$$Q_{tepl} = K \cdot F_b \cdot \left(t_t - t_{n.}\right), \quad (7)$$

where K is the coefficient of heat transfer of the insulation, W/(m^2·K); F_b is the area of insulation, m^2; t_t is the temperature of heat carrier, K.

Heat losses by the tank-accumulator, W:

$$Q_{b.a.} = K_{ak} \cdot F_{ak} \cdot \left(t_t - t_n\right), \quad (8)$$

where K_{ak} is the coefficient of heat transfer of the insulation of the tank-accumulator, W/(m^2·K); F_{ak} is the area of thermal insulation of the tank-accumulator, m^2; t_T is the temperature of heat carrier, °C.

Heat losses in the pipelines from a solar roofing to the tank- accumulator, W:

$$Q_{tr} = l \cdot \frac{\left(t_t - t_{n.}\right)}{R_k}, \quad (9)$$

where l is the length of pipelines, m; R_k is the linear thermal resistance to heat transfer of the pipelines, (m·K)/W.

By solving a system of equations (2), (3), (5)–(9), we received estimated values of temperature of the heat carrier in the process of irradiation of thermal-sensitive metal surface of the solar roofing by heat flow of varying intensity. Results are represented in the analytical form by a corrsponding equation (10) depending on the duration of irradiation

$$t_t = 10{,}6 + 0{,}6 \cdot 10^{-3} I_v + 0{,}7 \cdot 10^{-2} \tau - \\ -1{,}79 \cdot 10^{-8} I_v^2 + 2{,}61 \cdot 10^{-6} I_v \tau - 2{,}08 \cdot 10^{-8} \cdot \tau^2. \quad (10)$$

However, when using the numerical simulation, it is not possible to establish the influence of all factors and the non-stationary processes that occur in a solar collector and in the system as a whole. That is why, in order to determine energy efficiency of solar roofing in the system of solar heating supply, we have conducted experimental research.

Experimental setup was installed in the laboratory of National University “Lvivska Politekhnika” (Ukraine) and represents a fragment of solar roofing, the radiation source, tank-accumulator, measuring instruments and connecting pipelines.

Experimental studies were conducted under the following conditions, assumptions and simplifications:

– density of heat flow is accepted equal across the entire plane of the solar roofing;

– solar roofing was not shaded;

– influence of reflected solar energy from the surrounding objects was not considered;

– we accepted confidence interval of results of the experiment as α=0.95.

The main factors that affect the efficiency of solar roofing are:

x_1 – azimuth turning angle of the solar roofing, α, degrees;

x_2 – solar roofing incidence angle to the horizon, β, degrees;

x_3 – intensity of flow of thermal energy emitted from the source, I_v, W/m^2;

x_4 – velocity (V, m/s) of wind;

x_5 – wind direction (ψ, degrees).

To consider a simultaneous change of all 5 factors is quite a challenge, which is why to simplify the task, we proposed conducting experimental research in two stages.

At the first stage of research, the following variables were accepted:

x_1 (α=[30; 90]°);

x_2 (β=[30; 90]°);

x_3 (I_v=[300; 900] W/m^2),

in the absence of impact from factors:

x_4 (V=[2; 6] m/s) and x_5 (ψ=[0; 90]°).

In the second series, the following changed, respectively:

x_3 (I_v=[300; 900] W/m^2);

x_4 (V=[2; 6] m/s);

x_5 (ψ=[0; 90]°),

at constant values:

x_1 (α=90°) and x_2 (β=90°).

In order to improve efficiency of conducting the experiments and to bring down the costs on its arrangement, we have planned the experiment according to existing procedures [1, 7].

5. Results of examining the effectiveness of solar roofing depending on the incident angles of heat flow

We compiled planning matrix of a three-factor experiment, taking into account the interaction between factors (Table 1). Actual heat-absorbing capacity of solar collector first of all changes during daylight hours according to the incident angle of the heat flow on the surface of heat absorber. To evaluate the work of solar roofing, we selected as a parameter of optimization the efficiency coefficient of solar roofing K_{ef}, which shows how a change in the incident angle of rays influences effectiveness of the solar roofing.

$$K_{ef} = \frac{Q_i}{Q_{max}}, \quad (11)$$

where Q_{max} is the thermal energy that accumulated in the tank-accumulator at incident angles of the heat flow α=90° and β=90° and intensity of the heat flow I_v =900 W/m^2; Q_i is the thermal energy received by the solar system at different incident angles and intensity of the heat flow.

At stage I of the research, K_{ef} reflects the influence of incident angles and intensity of the heat flow on the effectiveness of solar roofing with a corrugated heat absorber.

Table 1

Planning matrix of the experiment

No.	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	K_{ef}
1	+	–	–	–	+	+	+	–	0.20
2	+	+	–	–	–	–	+	+	0.27
3	+	–	+	–	–	+	–	+	0.40
4	+	+	+	–	+	–	–	–	0.47
5	+	–	–	+	+	–	–	+	0.33
6	+	+	–	+	–	+	–	–	0.47
7	+	–	+	+	–	–	+	–	0.73
8	+	+	+	+	+	+	+	+	1.00

Key results of experimental measurements are represented in graphic form.

Fig. 2 shows a change in the temperature of heat carrier at input and output of the solar roofing and the ambient temperature during the experiment.

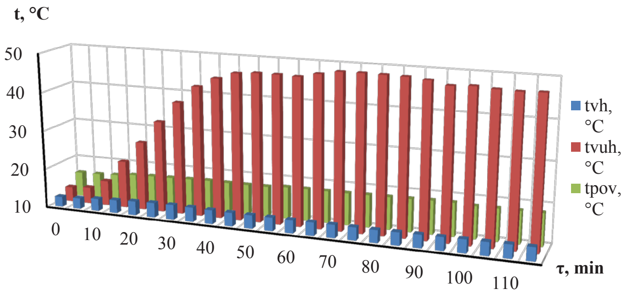

Fig. 2. Change in the heat carrier temperature at the input and output of the solar roofing and the ambient temperature during the experiment at intensity of the heat flow I_v=900 W/m^2 and at incident angle of the heat flow α=90°

We observe in the chart (Fig. 2) a sharp increase in the temperature of heat carrier at the output from the solar roofing over first 45 minutes of the experiment. During the experiment, temperature of the heat carrier increased by 36 °C.

A change in performance efficiency coefficient η of the system of solar heating supply with a solar roofing during the experiment is shown in Fig. 3.

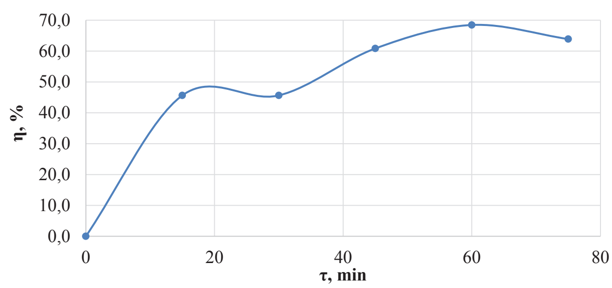

Fig. 3. Change in performance efficiency coefficient of the system of solar heating supply with a solar roofing during the experiment at intensity of the heat flow Iv=300 W/m^2 and at incident angles of the heat flow α=90° and β=90°

Chart in Fig. 3 shows that the performance efficiency coefficient of the system of solar heating supply with a solar roofing varies from 46 % to 69 %. In this case, the mean value of performance efficiency coefficient of the solar system is 58 %.

A change in the instantaneous capacity of solar roofing Q_h during the experiment at intensity of the heat flow I=900 W/m^2 and incident angle of the solar roofing β=90° is shown in Fig. 4.

$$Q_h = G \cdot c \cdot \left(t_{vyh} - t_{vh}\right), \quad (12)$$

where Q_h is the specific instantenous thermal capacity of solar roofing, W/m^2; G is the specific consumption of heat carrier, kg/(s·m^2); c is the specific heat capacity of the heat carrier, J/(kg·K); t_{vyh}, t_{vh} are the heat carrier temperatures at the input and output from the solar roofing, K.

When we analyze the graph in Fig. 4, we can see that the instantaneous capacity of solar roofing under the mode of gravity increases throughout the entire experiment and by the end of the experiment reaches 2200 W/m^2.

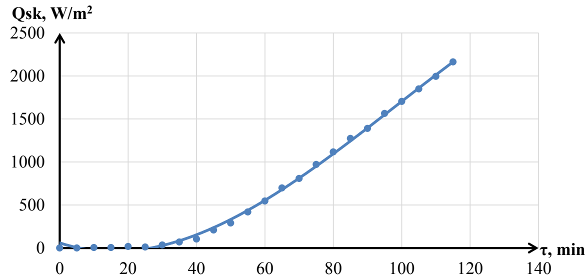

Fig. 4. Change in the instantaneous capacity of solar roofing Q_{sk} during the experiment at intensity of the heat flow I_v=900 W/m^2 and incident angle of the solar roofing β=90°

Processing the results of research employed known methods of mathematical statistics. Each experiment was accompanied by the emergence of error. To evaluate errors, each experiment was conducted several times, which is why we conducted a series of parallel experiments. Evaluation of reproducibility of the experiments came down to determining a dispersion of experiment reproducibility. Experiments were performed in a random sequence, which was established using a table of random numbers.

During the experiments, each experiment was performed three times, under the same conditions, in order to evaluate the errors. During each experiment, we received the values of a response function, which were averaged.

As a result of processing experimental data, we obtained a regression equation:

$$y = 0{,}48 + 0{,}07x_1 + 0{,}17x_2 + 0{,}15x_3 + \\ +0{,}02x_1x_2 + 0{,}03x_1x_3 + 0{,}07x_2x_3 + 0{,}02x_1x_2x_3. \quad (13)$$

The regression coefficients indicate how significant the impact of factors is on the response function and how a change in the factor affects a change in optimization parameter.

Upon determining the coefficients of regression, we verified significance. Test of significance of each coefficient was performed independently. It is possible to conduct it by the construction of confidence interval and by the Student t-criterion. When conducting a full factor experiment with effect of the interaction between factors, confidence intervals for all coefficients equal to one another.

First of all, we determined a variance in the regression coefficient by formula:

$$S^2(b_j) = \frac{S^2(y)}{N}. \quad (14)$$

Confidence interval was assigned by the upper and bottom boundary:

$$I_i=(b_i+\Delta b_i;\ b_i-\Delta b_i), \quad (15)$$

where b_i is the coefficient of regression; Δb_i is the possible error.

$$\Delta b = \pm t \cdot S(b_j) = t\sqrt{\frac{s_y^2}{N(n-1)}}, \quad (16)$$

where t is the tabular value of the Student criterion with a number of degrees of freedom at which we determined $S^2(y)$ and the chosen level of significance; $S(b_j)$ is the quadratic error of regression coefficient.

The coefficient will be significant if its absolute magnitude is greater than the confidence interval.

For a regression equation of efficiency of the solar roofing without transparent coating in the gravitational system of heat supply:

$$\Delta b = \pm 2{,}12\sqrt{\frac{0{,}00079}{16}} = \pm 0{,}014.$$

Therefore, all factors are significant and the regression equation will not change and will take the form:

$$y = 0{,}48 + 0{,}07x_1 + 0{,}17x_2 + 0{,}15x_3 + \\ +0{,}02x_1x_2 + 0{,}03x_1x_3 + 0{,}07x_2x_3 + 0{,}02x_1x_2x_3. \quad (17)$$

Based on an analysis of the regression coefficients, it can be stated that a significant impact on the behavior of a response function is exerted by factor x_2 (solar roofing incident angle β, °) and factor x_3 (intensity of the heat flow I_v, W/m^2). Factor x_1 (azimuthal turning angle of solar roofing α, °) does not affect it so substantially.

Using the results of experimental research, we constructed a nomogram of dependence of efficiency coefficient of solar roofing in the gravitational system of heat supply K_{ef} on incident angles of the heat flow α and β, and intensity of the heat flow I_v (Fig. 5).

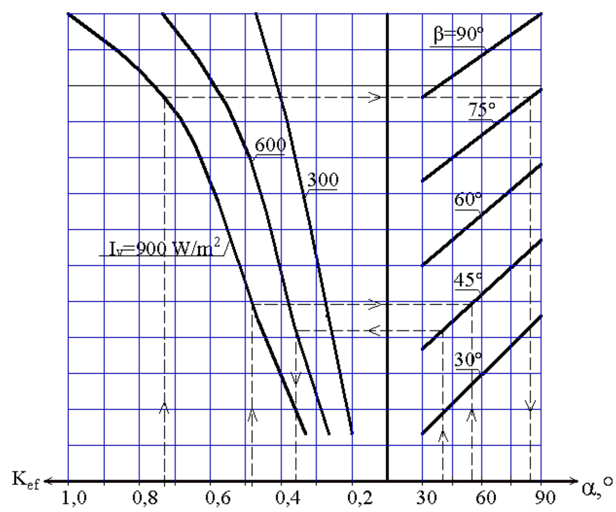

Fig. 5. Nomogram of dependence of efficiency coefficient of solar roofing K_{ef} in the gravitational system of heat supply on incident angles of the heat flow α and β, and intensity of the heat flow I_v

The nomogram (Fig. 5) is approximated by empirical dependence (18) of efficiency coefficient of solar roofing K_{ef} in the gravitational system of heat supply on incident angles of the heat flow α and β, and intensity of the heat flow I_v:

$$K_{ef} = \left(\begin{aligned} &(513 + 0{,}458 \cdot I_v) + (22 + 0{,}038 \cdot I_v) \cdot \beta + 12 \cdot \alpha + \\ &+(-0{,}019 + 6{,}389 \cdot 10^{-5} \cdot I_v)\beta \cdot \alpha \end{aligned} \right) \cdot 10^{-4}. \quad (18)$$

The absolute magnitude of coefficients of empirical dependence is greater than the confidence interval; therefore, equation (18) does not change.

6. Results of examining the effectiveness of solar roofing depending on the speed and direction of air flow

At the second stage of research, we chose K_{ef} as optimization parameter – the ratio of the amount of heat that a solar roofing received at different speeds and direction of air flow and intensity of the heat flow to the amount of heat that the solar roofing received at the least influence of wind.

Results of experimental measurements are given in a tabular form (Table 2) at intensity of the heat flow 300; 900 W/m².

Table 2

Amount of heat Q_{ak}, received by the heat supply system with a solar roofing in the gravitational system of heat supply at air flow velocity V=6 m/s and direction of air flow ψ=90° and intensity of the heat flow I_v =300 W/m², I_v =900 W/m²

Time, min.	Amount of heat $Q_{ak,}$ kJ	
	I_v=300 W/m²	I_v=900 W/m²
15	41.9	83.8
30	83.8	167.6
45	146.65	209.5
60	167.6	251.4

Table 2 shows a gradual heating of the heat carrier in the tank-accumulator throughout the entire experiment. At intensity of the heat flow I_v=300 W/m², the amount of accumulated energy in the tank-accumulator is 168 kJ. At intensity of the heat flow I_v=900 W/m² – 251 kJ, indicating effective work of the solar roofing.

A change in performance efficiency coefficient of the heating system with a solar roofing during the experiment is shown in Fig. 6.

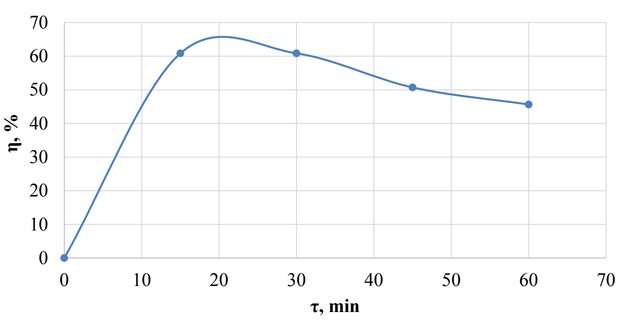

Fig. 6. Change in performance efficiency coefficient of heat supply system with a solar roofing during the experiment at intensity of the heat flow I_v=900 W/m², air flow velocity V=6 m/s and wind direction ψ=90°

The graph (Fig. 6) shows that performance efficiency coefficient of the system of solar heating supply with a solar roofing varies from 45 % to 61 %, and, after 20 minutes of the experiment, gradually decreases. The mean value of performance efficiency coefficient of the solar system is 55 %.

As a result of processing experimental data, we obtained a regression equation:

$$y = 0,716 - 0,099x_1 - 0,074x_2 + 0,124x_3 - \\ - 0,019x_1x_2 - 0,006x_1x_3 - 0,006x_2x_3 - 0,006x_1x_2x_3. \quad (19)$$

Using the results of experimental research, we constructed a nomogram of dependence of efficiency coefficient of the solar roofing K_{ef} in the gravitational system of heat supply on air flow velocity V, air flow direction ψ and intensity of the heat flow I_v (Fig. 7).

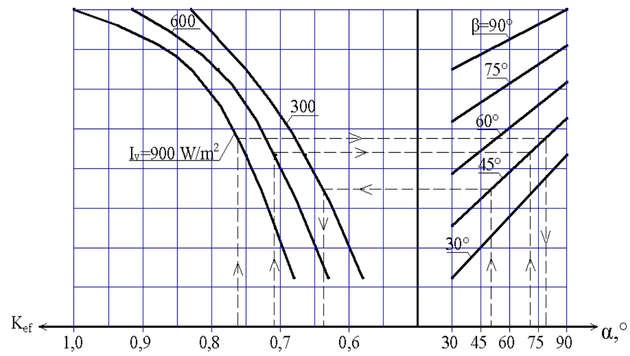

Fig. 7. Nomogram of dependence of the efficiency coefficient of solar roofing K_{ef} in the gravitational system of heat supply on velocity V, direction ψ of air flow and intensity of the heat flow I_v

The nomogram (Fig. 7) is approximated by empirical dependence (20) of efficiency coefficient of the solar roofing K_{ef} in the gravitational system of heat supply on air flow velocity V, air flow direction ψ and intensity of the heat flow I_v:

$$K_{ef} = \begin{pmatrix} (690 + 4 \cdot I_v) + (-10 + 3,333 \cdot 10^{-3} I_v) \cdot \alpha - \\ -40 \cdot V + (-3,333 \cdot 10^{-3} I_v) \cdot \alpha \cdot V \end{pmatrix} \cdot 10^{-4}. \quad (20)$$

The absolute magnitude of coefficients of empirical dependence is greater than the confidence interval; therefore, equation (18) does not change.

7. Discussion of results

One of the ways to overcome modern problems associated with a wide introduction of solar collectors into heating system is their combination with structural elements of the building.

Modeling of the work of a solar roofing confirms effectiveness of using solar roofing in the system of solar heat supply as temperature of the heat carrier at high intensity of heat flow 600 W/m² reaches 600 °C.

According to experimental studies, the mean performance efficiency coefficient of the heating system with solar roofing is 58 %. Temperature of the heat carrier at the output from the solar roofing by the end of the experiment reached 52 °C, which is a sufficient value for the system of hot water supply. A change in the speed and direction of air flow reduces efficiency of solar roofing by 20 %.

It was established that a larger impact on the energy efficiency of solar roofing with a transparent coating in the gravitational system of heat supply is exerted by velocity of air flow, while its direction is less influential. We can also argue that at numerical increase in the velocity and direction of wind, energy efficiency of the solar roofing with a transparent coating will decline due to increasing convective thermal losses.

8. Conclusions

1. Employing the developed mathematical model of the work of a solar roofing, we theoretically determined that at irradiation of the solar roofing during day hours by a heat flow of intensity 600 W/m^2, the heat carrier temperature reaches 63 °C.

2. We conducted laboratory research into solar roofing in the system of solar heating depending on the incident angles and intensity of the heat flow, velocity and direction of air flow. We received analytical dependences in the form of regression equations and empirical formulas, as well as graphic dependences, of effectiveness of solar roofing on the action of these factors. Using the results, it was found that the mean performance efficiency coefficient of the heating system with a solar roofing is 65 %, indicating the prospects of using solar roofing in solar systems.

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