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SUN ENERGY

Sehai O. M.

1. Solar Energy Resources

The local values of the sun's radiation energy coming to the surface of the lithosphere or hydrosphere depend on the orientation to the sun (luminoity), cloudiness, air dust, altitude, seasons and daytime. In the mid-latitudes in the afternoon, the intensity of solar radiation reaches 800 W/m in summer and 200…350 W/m in winter, decreasing to zero with the sunset.

The radiant energy of the sun has been used by the biosphere since the advent of life on the planet. The transformation of solar energy into mechanical energy was first demonstrated at the World's Fair in Paris, when a solar collector set in motion a steam engine.

Radiation from the Sun's surface is characterized by a broad energy spectrum, which roughly corresponds to the energy spectrum of blackbody radiation at 5800K. The maximum of the intensity lies in the visible region of the spectrum (0.35–0.75 μm), in which almost half of all energy is concentrated. The rest of the solar radiation is distributed between the ultraviolet part of the spectrum with a wavelength of less than 0.3 μm (smaller part) and the infrared with a wavelength more than 0.75 μm (bigger part). The intensity of solar radiation near the Earth's atmosphere is 1360 W/m2 – known as the solar constant AM0. When passing through the Earth's atmosphere, the intensity of solar radiation decreases due to its absorption, scattering and reflection during interaction with dust particles, oxygen, ozone, carbon dioxide, water vapor. When interacting with ozone and oxygen, the absorption of solar radiation occurs mainly in the ultraviolet part of the spectrum, water vapor and carbon dioxide absorb mainly in the infrared part. Therefore, the solar radiation that reaches the Earth's surface has less energy and its spectrum changes. The method of direct conversion of solar radiation into electricity is, firstly, the most convenient for the consumer, as it produces the most consumed kind of energy, and secondly, this method is considered to be an environmentally friendly means of generating electricity unlike others that use organic fuel, nuclear raw materials or hydraulic resources[1].

The average annual amount of total energy from solar radiation that enters the territory of Ukraine annually is in the range from 1 070 kWh/sq.m. in the northern part of Ukraine up to 1 400 kWh/sq.m. and higher in the Autonomous Republic of Crimea.

Photovoltaic equipment can operate efficiently enough throughout the year, however, as effectively as possible – for 7 months a year (from April to October).

The transformation of solar energy into electric power in the conditions of Ukraine should be oriented in the first place on the use of photovoltaic devices. The availability of significant reserves of raw materials, industrial and scientific and technical basis for the production of photovoltaic devices can to the full provide not only the needs of domestic consumers, but also export of more than two-thirds of the produced capacity.

As of 01.01.15, 98 solar plants with a total installed capacity of 819 MW operated in Ukraine, having generated 485 million kWh of electricity in 2014.

Taking into account the experience in the introduction of solar power plants (hereinafter – SPP) in European countries with similar levels of solar radiation, and also in view of the global tendencies of permanent decrease in the cost of construction of SPP due to technology development, in Ukraine due to the improvement of technology and commissioning of new facilities SPP electricity production can be significantly increased.

Roughly the territory of Ukraine can be divided into four zones depending on the intensity of solar radiation[2].

The experience of EU and North American countries shows that solar energy can be used on an industrial scale even at night. In Spain and the United States, there are businesses that, in the dark, generate electricity from the heat accumulated per day.

Solar-powered (solar) plants are completely silent. A significant drawback is that such stations occupy large areas. Each 1 MW of SPP capacity requires at least 1.5 ha of land. The disadvantage is that the energy output is inconstant. Today SPP accounts for about 4% of renewable electricity in the world. The transformation of solar energy into electrical energy is mainly due to the use of photovoltaic evements.

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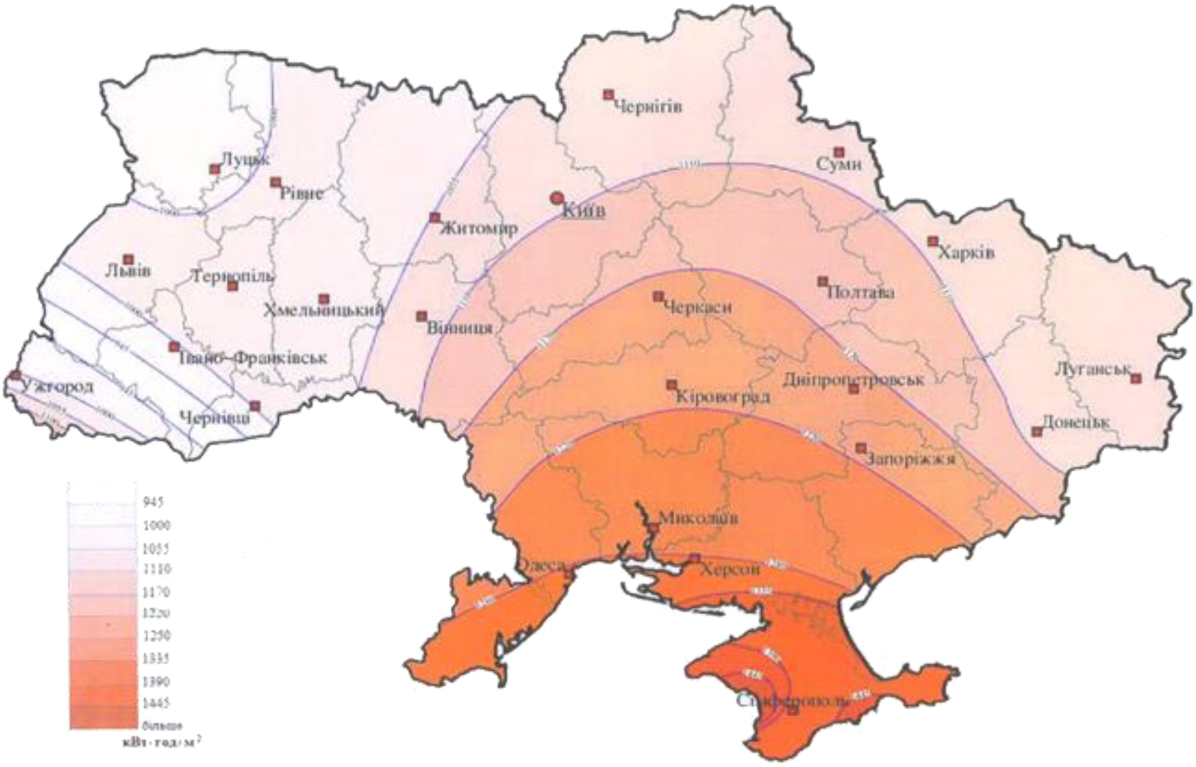
[1] URL: https://otherreferats.allbest.ru/physics/00097451_0.html
[2] URL: http://saee.gov.ua/uk/ae/sunenergy



Розподіл питомої сумарної сонячної радіації на території України протягом року
(Національний атлас України. – К.: ДНВП «Картографія», 2007)

With the help of the sun energy, it is possible to partially supply electricity to private sector residents (in parallel with the operation of the electricity grid). To do this, photovoltaic elements, located on the roof of the house, are used.

In private homes, solar collectors (SC) can be used to produce heat in a hot water supply system. Solar collectors are capable of heating water up to 70 °C. In the afternoon, the SC transforms the sun energy into heat, which heats the water that is accumulated in heat-insulated tanks (storage tanks). Water is supplied to the hot water supply system from the storage tanks. SC are installed on the roof of the house, and the storage tank and auxiliary equipment are installed in the technical room[3].

2. Solar-powered non-mechanical electrical installations

In non-machine solar power plants, the energy of the solar radiation is directly converted into electrical energy, without an intermediate transition into mechanical energy. Turbines and generators are not required for direct conversion.

[3] URL: http://saee.gov.ua/uk/ae/sunenergy

2.1 Thermoelectric transducers

The direct conversion of solar thermal energy into electricity is based on the Seebeck effect, which was discovered in 1821. If you connect two conductors of different chemical composition with the ends and place the solders in mediums with different temperatures, then thermoelectric power occurs between them:

$$E = \alpha \cdot (T_1 - T_2) \qquad (1)$$

where T_1 – the absolute temperature of the hot junction,

T_2 – absolute cold junction temperature,

α- proportionality coefficient.

A current *J*occurs in the conductor circuit, with hot junction absorbing heat from the heated source in the amount of $Q_1 = \alpha \cdot T_1 \cdot J$ per second, and cold junction giving heat to the low temperature body in the amount of $Q_1 = \alpha \cdot T_1 \cdot J$. The difference between the inlet and outlet heat is the instantaneous operation of the current

$$L = \alpha \cdot (T_1 - T_2) \cdot J, Bm. \qquad (2)$$

The ratio of work to the inlet heat is the thermal efficiency of the conversion process

$$\eta_t = L / Q_1 = \alpha \cdot (T_1 - T_2) \cdot J / \alpha \cdot T_1 \cdot J = (T_1 - T_2) / T_1. \qquad (3)$$

Thus, the efficiency of an ideal thermoelectric transducer coincides with the thermal efficiency of the Carnot cycle and is completely determined by the absolute temperatures of hot and cold junctions. In real transducers there are irreversible losses due to the electrical resistance of the conductors, their thermal conductivity and the thermal resistance of the heat transfer of the junctions with the environment. Therefore, the actual installation efficiency is equal to

$$\eta = \eta_{oe} \cdot (T_1 - T_2) / T_1, \qquad (4)$$

where η_{oe} <1 is the relative electrical efficiency of the transducer (named so by analogy with the relative internal efficiency of the turbine, which takes into account the irreversible throttle losses).

When using metal thermoelectrodes the efficiency of thermoelectric transducers is very small – it does not exceed one hundredth of a percent.

2.2 Photoelectric transducers

The principles of this type of installations are based on the principle of electrons being knocked out of semiconductor materials by light quanta. Radiation energy is converted into electrical energy. In modern solar energy semiconductor transducers of pure crystalline silicon are widely used. Silicon is a widespread element in the Earth's crust; sand, quartz are silicon dioxide SiO_2 . The production of pure silicon at the end of the twentieth century made it possible to adjust the production of a number of semiconductor devices, in particular processors for modern computers.

The power of the SPP with photoelectric transducers is determined by the ratio

$$N_{фе} = \eta_{фе} \cdot F_{фе} \cdot I, Bm, \qquad (5)$$

where $\eta_{фе}$ – efficiency of photoelectric transducers (varies in modern silicon elements within 0,12...0,17), $F_{фе}$ – their total square, m^2.

Industrial production of photovoltaic transducers, modules and solar power plants in Ukraine has quadrupled in the last three years. Solar energy is nowadays a serious alternative to traditional energy, since direct conversion of solar radiation to electricity is the most efficient use of solar energy carried out by means of semiconductor photoelectric transducers. Yes, the production cycle of Quasar OJSC is a positive example of the Ukrainian experience in forming a production chain, starting with the production of mono-multi-silicon and ending with the installation of systems. This enterprise is the largest industrial producer in Ukraine, which in its work covers the main part of the production cycle from growing semiconductor material to installation of finished photovoltaic systems of autonomous power supply. Also one of the largest participants in the market of "solar" silicon is the capital CJSC "Pillar" (more than 2500 tons per year), which supplies its products to many foreign manufacturers of solar elements.

The total amount of heat received by the solar energy steam generator is

$$Q = \eta_{в} \cdot n \cdot F \cdot I, Bm, \qquad (6)$$

where $\eta_{в}$ – the coefficient of efficiency of the use of solar radiation (varies within 0.35...0.5), n – number of heliostats,

F – mirror square of one heliostat, m^2,

I – intensity of solar radiation, W/m^2.

The wwork of 1 kilogram of steam in a steam turbine unit in the Rankine cycle is equal to

$$I = h_1 - h_2, кДж / кг. \qquad (7)$$

Thermal Efficiency:

$$\eta_t = (h_1 - h_2) / (h_1 - h_k), \qquad (8)$$

where h_1 – enthalpy of hot steam,

h_2 – enthalpy of steam exhausted in the turbine (determined by h – s diagram of water vapor), h_k – enthalpy of condensate (determined by the tables of thermodynamic properties of water and water vapor).

The theoretical power of the steam turbine of ST will be:

$$N_{nm} = \eta_t \cdot \eta_{oi} \cdot \eta_e \cdot QBm, \qquad (9)$$

where η_{0i} – relative internal efficiency of the turbine,

η_e – efficiency of the generator (within 0.92...0.96).

The actual capacity of the SPP is less than the theoretical capacity due to energy consumption for own use (pump drive, etc.).

3. Solar heat supply

Solar water heaters have been used for heating and hot water supply since the beginning of the twentieth century. Up to now, due to state-supported energy-saving programs in a number of countries (USA, Germany, Norway) solar collectors, installed on the roofs or glazed porches and made of polymeric plastics with glass, are widespread.

The device of the solar module-water heater is very simple. A flat screen with tubes welded from below is illuminated by sunlight. Tubeless screens are also used, in the form of two plates with a gap between them. The screen is connected by tubes to the top and bottom of the storage tank. The natural circulation is installed in the circuit: cold water enters the pipes from the bottom of the tank, the water heated in the pipes of the screen with lower density flows into the upper part of the tank. The top of the screen is painted with black matte paint to increase the coefficient of absorption of the radiant energy, and covered with glass or polymer membrane to protect from precipitation. In regions with negative temperatures, the circuit is filled with an aqueous antifreeze solution; solar-heated antifreeze gives heat to the water of the storage tank in a tubular heat exchanger.

Solar energy can be used to desalinate seawater and polluted water. The simplest solar distiller is a reservoir filled with a layer of salt water of small thickness; the sun's rays concentrated on the reservoir evaporate the water. The steam condenses on an inclined flat wall, and the condensate flows into the water desalination tank. Solar refrigeration units have also been developed, in which the refrigerant (ammonia) is evaporated by solar radiation and further participates in the operation of the absorption type refrigeration cycle.

4. Solar installations. General characteritics

Solar collectors are designed to convert solar energy into thermal to heat water for domestic use and to support the heating system. Thanks to design improvements and high absorption coefficient (95%), solar collectors are effectively running for almost 9 months a year. The collector glass is impact resistant and guarantees mechanical resistance to precipitation (hail) or solid objects' hits. The use of non-freezing liquid (glycol solution) ensures the operation of the collectors at low air temperatures up to minus 30 °C. Solar thermal systems, if properly designed and properly installed, are considered to be one of the most reliable and durable.

The main types of solar water heaters are flat and tubular vacuum collectors, thermosyphon solar systems.

Flat collectors are widely used all over the world; they are slightly cheaper than vacuum tubular collectors.

Thermosyphon solar systems are used seasonally – from spring to autumn. But there are already constructive modifications of thermosyphon systems for use throughout the year, but in the absence of heavy frosts.

The flat collector is a well-insulated glass panel that houses a solar heat absorber plate and tubes with circulating fluid to remove the heat generated.

This plate has a special highly selective coating that absorbs solar energy well. The lower plate and side walls of the collector are covered with heat insulating material. But despite this, the heat losses of the flat collectors on the glazed side are quite considerable, especially in winter with a considerable difference between the temperatures of the coolant in the collector and the outside air. The heat flux from the sun enters the plate, that heats up converting solar radiation into thermal energy, which is transmitted to the coolant. To improve the perception of solar radiation, absorbers are made with a selective coating. The selective coating consists of a thin membrane of filter (nickel, titanium) deposited on a metal substrate that conducts heat well (copper, aluminum) and is characterized by high absorption capacity in the visible region of the spectrum and low radiation coefficient in the infrared region.

The designs of vacuum **tubular collector**have different modifications but in principle are similar to the construction of a thermos: one glass tube is placed in another, of a larger diameter, and between them there is vacuum, the best heat insulator.

Thermosyphon solar systems are used to compensate for seasonal heat loads – work in the warm months of the year, for the preparation of hot water for heating water in outdoor pools, summer boarding houses and guest houses, etc.

This installation is installed on any sunlit area in the south direction, and is connected to a conventional pipeline system (like a regular electric boiler). The use of multilayer coated vacuum tubes and heat pipes more efficiently ensures the transfer of heat to the water and will ensure the continuity of operation of the device even in case of failure of several vacuum tubes.

Solar collectors are installed at an angle equal to the latitude angle on the south side. Mounting directly on the roof is possible. The angle of rotation of the collector towards the south orientation is also taken into account. There are many schemes for the implementation of solar systems, both separately functioning and those that are connected to the existing system of hot water supply and heating.

5. Technological aspects

The examples of circuit solutions and the composition of solar systems.

Solar collector converts solar energy into thermal energy. The heat is extracted by pumping through its channels the liquid coolant. The collectors must be oriented in the south direction (tolerance without significant reduction in efficiency is up to 60°).

Heat exchanger tank-battery. The peculiarity of solar heating systems is the need to accumulate solar thermal energy in order to use it at different times of the day. This can be done by using the tank-battery system.

In such systems, the circulation is carried out due to the difference in the densities of cold and heated water. As a consequence, the storage tank in such systems should always be located above the panels of the solar collectors. Such systems are made open. Open systems are systems in which water for hot water supply systems is directly heated in the solar collectors.

Advantages:

- simplicity of construction;
- easy installation, due to the modular construction, it is possible to install independently;
- reliability of work;
- low cost;
- possibility of heating water to high temperature;
- energy independence

Disadvantages:

- the need for water purification due to the possibility of formation of deposits in the collector tubes;
- limited use due to the possibility of system freezing in winter.

In open systems, the circulation is carried out by means of electric pumps.

Advantages:

- possibility of execution of HWS system of any capacity;
- possibility of arrangement of the storage tank in any convenient place (as a rule, basement);
- no risk of unfreezing of the storage tank;
- possibility of successive connection to the installation of the boiler unit or introduction of the electric heater directly into the storage tank for additional heating of water in the cold period.

Disadvantages:

- higher cost than of the previous scheme;
- more complex installation;

- energy dependence;
- the need for water purification due to the possibility of formation of deposits in the collector tubes;
- limited use due to the possibility of system freezing in winter.

Closed systems are systems in which the intermediate coolant is heated. As a coolant, as a rule, non-freezing liquids based on glycols are used, which allows to exploit the reservoirs in winter.

Advantages:

- possibility of execution of HWS system of any capacity;
- possibility of arrangement of HWS boiler in any convenient place;
- the possibility of full-fledged work throughout the year in case of the use of freezing coolant in the first circuit;
- possibility of combining the device with the boiler unit for hot water heating.

Disadvantages:

- high cost;
- lower energy efficiency due to additional heat exchanger;
- the need to involve qualified installers, due to the greater complexity of the system;
- energy dependence.

Initially, the most popular solar collectors in Ukraine are the ones for hot water supply needs in the private residential sector. Although, the scope of solar energy in our country is much wider.

The controller is a mandatory element of solar systems with forced circulation of coolant. It monitors the state and controls the solar heating process of the solar system, and can control other thermal processes in the general system. The controller receives information from the temperature sensors and selects the required operating mode. The efficiency and security of the solar system depend to a large extent on the controller, its algorithms, the reliability of the elements.

The pumping station is used in systems with forced circulation (such a system is 30% more efficient than a system with natural circulation) and is intended to ensure the circulation of coolant in the collector circuit. The hydraulic resistance of the collector circuit is quite small, which makes it possible to use low-power pumps whose power consumption is negligible compared to the received thermal energy from solar collectors.

Pipelines and thermal insulation. Metal pipelines need to be used, so all known plastic pipes do not withstand the possible operating temperatures (maximum steam temperature in the circuit, even in inefficient solar collectors can reach 150 °C, and the operating temperature of the coolant can reach 110 °C). For the same reason, the requirements for pipe insulation are increased, which must withstand high temperatures, as well as not absorb moisture or shrink. Thermal insulation of foamed rubber meets all requirements. To ensure a sufficient reduction of thermal losses in the pipeline, as well as for safety purposes, thermal insulation must be at least 19 mm thick. It is forbidden to use thermal insulation made of foamed polyethylene applied directly to the pipe without a temperature suppression layer. The pipe diameters are selected individually based on the required hydraulic resistance of the system and the flow rate of the coolant. Possible system parameters and pipe diameters must be consistent with the parameters of the pumping stations.

Expansion tanks. Due to the fact that the solar collector circuit is closed, expansion tanks with a working pressure of 6 atmospheres (max. 10 atm.) must be used to compensate for the change in the volume of the liquid during the temperature change. With nitrogen cushion to increase membrane life.

Support metal structures are made of corrosion-resistant materials (stainless steel or anodized aluminum) and are designed for a wind speed of 30 m/s.

6. Equipment and layout calculation methodology

Modern heating and HWS systems due to the uneven supply of solar energy in different periods of the year are not able to fully meet the demand for thermal energy, that is, at the right time of the right temperature in the required amount. To act in terms of fuel economy and environmental protection means that the use of a solar collector installation should be planned not only for hot water preparation but also for the heating system.

A solar installation can only work if the coolant temperature drops below the temperature of the solar collector adsorber. Therefore, the best option is to use it for heating devices with a large heating area and low temperatures in the system or for floor heating.

Solar collectors use total solar radiation, which consists of direct, scattered, and reflected, to heat the coolant. The density of direct solar radiation flux in the collector plane $H_{пр}$ to the surface inclined at an angle to the horizon is equal to:

$$H_{пр} = H_{sc} \cdot R_{пр} \cdot K_{ат}, \tag{10}$$

where $R_{пр}$ is the conversion coefficient of direct solar radiation arrival from the horizontal to the inclined surface;

$K_{ат}$ is a coefficient that takes into account the correction for the air mass the sun's radiation goes through.

The conversion coefficient of direct solar radiation arrival from the horizontal to the inclined surface is equal to:

$$R_{пр} = \frac{\cos\theta_{пох}}{\cos\theta_{гор}} \tag{11}$$

where $\theta_{пох}$ is the angle between the direction of direct sunlight and normal to the inclined surface;

$\theta_{гор}$ - the angle between the direct sunlight direction and the normal to the horizontal surface.

$$\begin{aligned}\cos\theta_{пох} &= \sin\delta\cdot\sin\varphi\cdot\sin S - \sin\delta\cdot\cos\varphi\cdot\sin S\cdot\cos\varphi + \\ &+ \cos\delta\cdot\cos\varphi\cdot\cos S\cdot\cos\omega + \cos\delta\cdot\sin\varphi\cdot\sin S\cdot\cos\gamma\cdot\cos\omega + \\ &+ \cos\delta\cdot\sin S\cdot\sin\gamma\cdot\sin\omega,\end{aligned} \tag{12}$$

$$\cos\theta_{гор} = \sin\delta\cdot\sin\varphi + \cos\delta\cdot\cos\varphi\cdot\cos\omega, \tag{13}$$

where S – angle of the solar collector incline to the horizon, deg;

γ is the azimuthal angle, that is, the deviation of the normal to the collector plane from the local meridian (the south direction is taken as the beginning of the reference, the deviation to the east is considered positive and the one to the west is negative);

ω is a time angle equal to zero at noon; each hour is equal to 15 ° longitude, with the value of time until noon is considered positive and the one after noon is negative;

δ is the Sun's inclination, that is, the angular position of the Sun at noon relative to the plane of the equator, deg;

φ – latitude (positive for the northern hemisphere).

The time angle ω is calculated by the formula

$$\omega = \frac{\pi}{12} \cdot (12 - t), \tag{14}$$

where t is the solar time for the area, h.

The Sun declination is calculated as follows:

$$\delta = 23 \cdot 45 \cdot \sin\left\{\frac{2\pi}{365}(284 + N)\right\}, \tag{15}$$

where N is the ordinal number of the day of the year (starting from 1, corresponding to January 1);

The coefficient K_{am}, which takes into account the correction for air mass, is given by the formula:

$$K_{am} = 1{,}1254 \cdot \frac{0{,}1366}{\sin h}, \tag{16}$$

where *h*is the angle that determines the height of the sun above the horizon at a given time, deg., the sinus of this angle is equal to:

$$\sin h = \cos\delta \cdot \cos\omega \cdot \cos\varphi + \sin\delta + \cos\varphi. \tag{17}$$

Formula (4.10) allows to calculate only the amount of direct solar radiation flux directed to a random surface. However, any solar collector also experiences the effect of scattered solar radiation. The exact calculation of this component of the energy supplied to the solar collector is quite complicated. However, with sufficient accuracy for a randomly located surface, this value can be approximated by empirical dependence:

$$H_{розс} = 137{,}1 - 14{,}82 \cdot \frac{1}{\sin h}. \tag{18}$$

The reflected solar radiation can be estimated from the expression:

$$H_{від} = 0{,}5 \cdot \rho \cdot (1 - \cos S) \cdot (H_{пр} + H_{розс}), \tag{19}$$

where ρ – reflective property of the Earth;

$\rho = 0{,}2$ in summer;

$\rho = 0{,}7$ in winter with snow.

Finally, the total energy flow brought by solar radiation to a randomly space-oriented inclined surface at latitude L is equal to:

$$H_{т} = H_{пр} + H_{розс} + H_{від}. \tag{20}$$

It should be borne in mind that all these values are given for a clear day, in practice, when calculating the so-called cloud factor should be taken into account. It should also be noted that the calculated flow values for different hours are almost exactly the same as those given in the tables in the regulatory documents (Building rules and regulations) and the climate atlas.

Solar systems that provide heat demand are divided into *active* and *passive*. Passive systems that use architectural elements that are designed to maximize the use of solar energy are less expensive and do not require additional equipment. The active ones are built on the basis of solar collectors (SC) with forced circulation of the coolant by means of pumps. Flat solar collectors capture both direct and scattered solar energy and allow you to obtain water at a temperature of 40…60 °C. The seasonal efficiency of simple passive solar systems may be no less effective compared to more sophisticated and expensive solar thermal supply systems.

The disadvantage of passive systems is the complexity of regulating indoor air temperature and the need to use self-regulating devices.

Active solar systems can use non-freezing air or liquid (antifreeze) as coolants. The advantage of active systems is the ease of integration with traditional heating systems, as well as the ability to automatically control the operation of the system, and the main disadvantage is the high cost. The choice, composition and layout of the elements of the active system is determined in each case by climatic factors, object type, heat supply regime, economic indicators. Due to the fact that it is difficult and expensive to maintain the surface of the solar collector perpendicular to the sun rays, the solar collectors are installed fixed or they change orientation twice a year. It is best to orient the collectors to the south. The optimal angle of inclination of the collector to the horizon is:

– $S = \varphi + 12°$, – for summer (seasonal) operation;

– $S = \varphi - 12°$, – for year-round operation.

where φ is the latitude.

Solar installations are of two types: of *seasonal* and *constant use*. In the solar collector of seasonal type, the water is heated directly in the solar collector, and in installations of constant use the water is heated in the tanks of indirect year, as an intermediate coolant uses antifreeze, which perceives the sun energy in the solar collector.

The mode of operation of the solar collector is described by the equation of energy balance, which divides the energy of solar radiation into useful accumulated energy and losses. The energy balance of the collector as a whole can be written in the following form:

$$A\{[H_R(\tau\alpha)]_b + [H_R(\tau\alpha)]_d\} = Q_u + Q_L + Q_S, \qquad (21)$$

where H – the density of the flux of solar radiation (direct or scattered) incident per square unit of the horizontal surface;

R – coefficient of recalculation of direct or diffuse radiation density from horizontal to inclined surface;

τα is the absorbing property of the coating system with respect to direct or scattered radiation;

A – collector square;

Q_u – the heat flow that is transferred to the working fluid in the solar collector (useful heat);

Q_L – thermal losses of the collector to the environment by radiation and convection, as well as by thermal conductivity on the resistances of the absorbing plate, etc .;

Q_s – the heat flow accumulated by the collector.

An indicator of the efficiency of a solar collector is its efficiency – the ratio of useful thermal energy Q_u to incident solar energy.

For testing solar collectors they often use the methodology of the US National Bureau of Standards. According to this method, the test is carried out on an experimental bench in a stationary environment, when solar radiation, wind speed, ambient temperature for some time.

The tests are carried out either in the natural environment at about noon on sunny days, or using a solar simulator.

The useful energy from the collector is determined by the expression

$$Q_u = F_R \cdot A \cdot [I_T(\tau\alpha) - U_L(T_i - T_a)], \qquad (22)$$

where *FR* – coefficient of heat removal from the collector;

IT – total solar radiation flux density in the collector square, W/m²;

τα – reduced absorption capacity (also takes into account that part of the radiation that passed through the glass coating, reached the adsorber, and returned to the glass again):

U_L – full heat loss coefficient of collector W/(m^{2}K);

T_i – fluid temperature at the inlet to the collector, °C;

T_a – environment temperature, °C;

The test results determine the efficiency of the collector

$$\eta = \frac{Q_u}{A \cdot I_T}. \tag{23}$$

The collector heat capacity can be also determined by the temperatures of the coolant at the inlet and outlet of the collector by the formula:

$$Q_u = G \cdot C_p (T_o - T_i), \tag{24}$$

where G is the mass flow rate of the coolant, kg/s;

C_p – specific mass heat capacity of the coolant, J/(kgK);

T_o, T_i – coolant temperatures at the outlet and inlet of the collector absorber, °C.

The efficiency coefficient can be also determined as follows:

$$\eta = F_R(\tau\alpha) - \frac{F_R \cdot U_L (T_i - T_a)}{I_T}, \tag{25}$$

where $FR(\tau\alpha)$ is a component coefficient showing the maximum theoretical efficiency value for this solar collector structure;

$F_R U_L$ is the component coefficient characterizing the thermal losses of a particular collector srtucture.

The coefficient found by formula (3.26) largely characterizes the structural and thermal perfection of the flat solar collector structure. In the equilibrium state (no coolant circulation), the collector is heated to the maximum temperature when there are the intensity of sun radiation and environmental temperature. The equilibrium temperature is to some extent a characteristic of the collector thermal efficiency (collector heat losses).

The density of absorbed converted energy is calculated by the formula:

$$q = \frac{E}{A}, \tag{26}$$

where $A$is the working square of the collector surface, m² [4,5,6,7,8].

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The coolant temperature at the inlet to the collector has a great influence on the value of the solar collector efficiency: the lower the temperature, the lower the heat losses and the higher the efficiency. According to the experience of operating flat solar collectors, increasing the flux density of solar radiation from 300 to 1000 W/m² leads to an increase in the efficiency from 32 to 59%, and when the environment temperature increases from 20 to 30 °C, the efficiency increases from 41 to 55%.

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Information about the author:
Sehai O. M.
Candidate of Technical Sciences, Associate Professor,
Associate Professor at the Department of General Engineering
Disciplines and Thermal Power Engineering
of the V. I. Vernadsky Taurida National University

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