Напрямом дослідження є синтез системи тригенерації для «сонячного будинку» на базі автономної малої сонячної фотоелектричної станції, здатної задовольнити приватних споживачів цілорічним отриманням електроенергії, тепла та холоду.

Для аналізу використано кліматичні дані країн Близького Сходу Ірану, Саудівської Аравії. Об'єднаних Арабських Еміратів,Туреччини, Сирії, Іраку. Визначено денні та нічні температури повітря на протязі року у різних регіонах вказаних країн та сумарну добову радіацію, яка надходить на горизонтальну поверхню територій. Одержані результати визначили, що уся територія Близького Сходу придатна для розвитку сонячного енергопостачання. Сезонні та добові коливання температури повітря потребують цілорічне використання штучного холоду для кондиціювання та опалення житлових приміщень. На підставі проведеного аналізу синтезовано узагальнене схемне рішення малої інтегральної системи тригенерації, яка базується на фотоелектичній сонячній станції. Гаряче водопостачання забезпечують додаткові сонячні колектори з водонагрівачем-акумулятором. Кондиціювання повітря та опалення здійснює холодильна машина. Терміни зміни режимів визначаються температурою навколишнього середовища, яка не співпадає з комфортною в конкретному приміщенні. Температурний режим в приміщенні підтримує потік свіжого повітря з системи активної вентиляції, охолоджений або підігрітий в теплообмінних апаратах машини. Для узгодження роботи всіх елементів системи розроблено інструментарій для визначення теплових навантажень та температурних режимів у приміщенні та елементах системи тригенерації. Дослідження дозволяє стверджувати,що «Сонячні будинки» здатні вирішувати енергетичні, екологічні проблеми регіонів, забезпечити соціальні потреби населення країн Близького Сходу

Ключові слова: сонячний будинок, фотоелектрична станція, тригенерація, компресорна холодильна машина, активна вентиляція

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SYNTHESIZE OF THE INTEGRATIVE TRIGENERATION SYSTEM FOR A «SOLAR HOUSE» IN THE MIDDLE EAST REGION

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1. Introduction

The UNESCO Conference in Paris in July 1973 was held under the motto "The sun at the service of a man". The entirely accurate information about the state of the solar energy in the world was formulated: solar energy from an object of scientific research has become a new branch of industry, an important issue for the whole humanity. It is of professional interest for scientists, engineers, builders, power engineers and of economic interest for private consumers who must pay for excessive power consumption.

There are a lot of implemented projects of using solar energy in the world. They have practical application in countries with the warm climate (the United States, Japan, India), in countries with temperate climate (France, England, Germany) and in many northern regions (Sweden, Finland, Canada, and Alaska) [1]. The pace of the development of solar energy engineering is increasing dramatically worldwide. The World Solar Commission of the United Nations Organization adopted a ten-year program of development of the world solar power engineering, recommended for implementation in all countries [2].

When it comes to the Middle East, according to experts' evaluation, this region has one of the best natural potentials in the field of photovoltaics, since most of the countries of this region have vast areas of unpopulated territories receiving intense and lengthy sunlight. At the same time, solar energy in this region is not used widely enough [3]. Regardless of the reasons, existing in each particular country, solar energy engineering begins to occupy its niche in the Middle Eastern electric power markets. In the long-term prospects, there is no doubt that solar energy will play a very important role in the energy balance of the region. The extent and terms of the growth of the solar market depend on many factors. Taking into consideration the uncertainty existing in the solar energy markets in the Middle East countries, it is possible to say that the research aimed at the long-term development of this energy sector can be considered relevant.

The solar energy engineering is developing in the following directions: conversion of solar energy into thermal energy for heating and hot water supply and direct conversion of solar energy into electricity (photovoltaic converters). Systems of heat, cold and power supply (trigeneration) created based on solar power rationally integrate the capabilities of the system of cooling and air conditioning. It should be noted that the year-round air conditioning (seasonal heating and cooling) is a primary consumer in many countries of the world and ensures the stable operation of the trigeneration system.

Over the past twenty years, the scientific and technical idea of a "solar house" – building complexes from a private cottage to a small settlement or a hotel, the power needs of which are provided by the sun, has been intensively developed. A house, equipped with a special solar plant, can completely provide itself with power. All experts believe that the main achievement of "solar" construction is socio-environmental effect.

In many advanced countries, development of "solar" construction is one of the directions of the state policy. Large companies engaged in the construction of such houses were set up. The variety of designs of solar systems led to the emergence of specialized enterprises that produce equipment and materials for them. The UNESCO, the European Commission, the United Nations, and the Department of energy of the United States deal with the issues of energy-saving construction. The International solar energy society ISES, the world organization of the development and spreading of energy technologies, was created, and is functioning successfully.

2. Literature review and problem statement

"Solar houses" are classified based on the type of the applied solar energy system [4]:

– with a passive solar system;

– with an active solar system;

– with an active solar system equipped with a heat pump.

The "solar houses" with a passive solar system include only those houses that use solar energy for heating and hot water supply. A passive system of solar heating is based on direct heating by sunrays and natural air circulation.

An active system is an engineering system, which consists of the following main components: a receiver and a converter of solar energy into thermal energy; a heat accumulator; a heating device; heat distribution systems.

An active system is characterized by multi-functionality. It can be used for heating, cooling, and hot water supply. Cooling is performed by absorption refrigerating machines, the primary energy for which is thermal energy. It became one of the advantages of the houses with an active system. In these houses, there are no specific requirements for mutual location of premises. However, the architecture is determined by the character of location of solar cells in relation to the volumetric structure of a building.

Solar houses with a mixed system (active + passive) were selected from the group with an active system of solar heating and named integral [5]. Solar houses with the integrated system have their own specificity, characteristic space-planning solutions of a house, inherent of the group with both passive and active systems. In buildings with the integrated system, effectiveness and flexibility of the active system is combined with reliability and simplicity of passive systems.

The operation of "solar houses' in warm seasons of the year requires enhanced natural ventilation of a building to protect it from overheating. The paper contains the recommendations for air exchange, which is established at 0.5 of the total volume of the building per hour. Good organization of air flows in a building is carried out by natural convection. This is achieved by the creation of vertical air flows. The use of the "solar pipe" principle is the basis for all design solutions.

An active system includes buildings with solar photovoltaic energy plants. Regulated automation, a computer, controlling heat and light modes of house and other high-performance facilities provide maximum absorption of solar energy. One of the problems hindering a widespread use of photovoltaics is the relatively high cost of photovoltaic devices.

Thermodynamic and economic analysis of applying solar heat-using absorption chillers and compressors driven by a photovoltaic plant for commercial consumers, having cold performance of 10 kW/per day was performed in paper [6]. The comparison involved three types of absorption machines with different temperature potential of solar collectors, water and air cooling the corresponding heat exchangers. Thermodynamic analysis revealed high thermodynamic efficiency of a compressor machine by the COP indicator, economic analysis showed the benefits of two-stage absorption system by OSE (Overall System Efficiency). Introduction to the analysis of the new prices for photovoltaic converters and increased values of their effectiveness demonstrated the benefits of photovoltaic technologies with compressor chillers with air cooling of heat exchangers, according to OSE.

Photovoltaic systems are divided into two main types: autonomous and those connected with the industrial electrical network. Autonomous systems, according to operation information [7], supply power to the mobile sites or those remote from the main supply lines. Small photovoltaic station produces electricity only in the light daytime. An accumulator is used for storage at night. An autonomous photovoltaic station provides a stable all-day power supply to a private consumer of lighting, using household appliances, air conditioning and heating in residential premises in the absence of a centralized energy supply. At frequent breaks in electricity supply in central networks, an autonomous solar system with direct energy conversion is used as an emergency source of energy.

"Solar houses" are based on the autonomous solar system of power supply. The system consists of the following components: a solar cell of the required power from photovoltaic modules; a controller of charge of accumulator; accumulators' battery; an inverter, which converts DC into AC for power supply of household electrical appliances.

Availability of electrical energy contributes to the creation of the trigeneration system with obtaining heat and cold with the involvement of compressor refrigerating machines and heat pumps. In this case, a "solar house" acquires the status of the integrated trigeneration system with a single type of primary energy – solar energy. "Solar houses" can be referred to the small autonomous power engineering, the main feature of which is the independence on regional energy companies and monopolists in the market. Over recent years, the authors pay attention to some sufficiently authoritative research into the problems of introduction of solar photovoltaics for production of cold and air conditioning using compressor refrigerating machines.

Paper [8] explored a conditioner with the compressor refrigerating machine driven by an autonomous photovoltaic energy plant. The circuit of an air conditioner includes an ice accumulator, a pump, and a fan coil. Two operating models of a photovoltaic plant were experimentally studied: one with a controller and an inverter, the other with an additional accumulator. The units of solar modules ensured the operation of an air conditioning system at large starting currents and the operation of an ice accumulator when the operation of a refrigerating machine stopped. The research results showed that the solar energy, received by photovoltaic modules was fully absorbed by an ice accumulator. Specifically, according to the authors, the analysis of the experiment results showed that it is appropriate to "store" solar energy with the autonomous photovoltaic cooling in an ice accumulator rather than in the accumulating battery.

Paper [9] considered the system of heating and cooling for residential and public buildings in the Southern and Northern Europe powered by solar energy and promising alternative energy sources. It was concluded that the cycles of compressor refrigerating machines driven by photovoltaic power stations have the most cost-effective solutions due to the high thermodynamic perfection of a machine. The second-best option is the recognized drive from a parabolic solar collector or the Stirling drive. The attention was drawn to the fact that the investments in systems with solar drive are smaller, if a refrigerating machine has air heat exchangers.

Research in paper [10] was conducted to assess the technical and economic potential of transforming an ordinary household refrigerator with alternating current into direct current with the drive directly from the PV plant without an inverter. The main conclusions of this study are the following: In a refrigerator, temperature modes and cold productivity remain constant at the replacement of engines. Experimental measurement of starting power, consumed by the AC engine, shows high jumps that are by 2…3 times higher in comparison with a relatively small pulse power of a compressor with the DC engine. High pulse power of an AC compressor requires high-performance of inverters and, therefore, high costs of the system for running the AC refrigerator on the solar photovoltaic system. The results of the research indicate that the use of refrigerating machines with DC compressors have the potential to reduce the total costs of photovoltaic plant approximately by 18 %.

The considered papers and studies deal with one important problem – the interaction of characteristics of an autonomous photovoltaic plant with the characteristics of a compressor machine. It is about the types of engines of compressors with direct and alternating current, which affect energy and economic indicators of the entire system. Thermodynamic cycles of refrigerating machines are considered at the theoretical level (the Plank cycle) in modes of moderate temperatures and low power. Information about solar houses with small thermal solar plants regards the systems of heating and hot water supply under conditions of temperate climate. Solar houses with photovoltaic units are represented by the illustrative material of the location of solar cells relative to a building and methodological clarification for determining the surface of solar cells.

The considered scientific information is needed for the development of solar energy engineering, but its further advances can be associated with the use of a solar photovoltaic energy plant with year-round full load on electricity with the constant consumption of cold and heat, which is determined by the climatic conditions of the area. Under such conditions, it is possible to achieve a significant environmental, economic, and social effect. The territories of North Africa and the Middle East with the tropical and sharply continental climate meet these conditions.

3. The aim and objectives of the study

The aim of this research is the synthesis of the integrated trigeneration system based on an autonomous photovoltaic station, capable to satisfy private consumers with year-round supply of electricity, heat and cold.

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

– to analyze the climatic conditions of the Middle East countries;

– to synthesize the generalized technological scheme of a small trigeneration system;

– to synthesize toolset for determining thermal loads and temperature modes in premises and elements of the trigeneration system.

4. Analysis of climatic conditions in the Middle East countries

The intensity of solar energy depends on the geographical latitude of the area, climatic conditions in different seasons. On a clear day, the flow of solar radiation, which reaches the Earth's surface, taking into consideration reflection, absorption and scattering by the atmosphere, can reach 75…90 % beyond the atmospheric flow of solar radiation, and in cloudy weather – 5 %.

For practical calculations, it is possible to recommend the data on total daily radiation, which arrives onto a horizontal surface in different regions of the Middle East countries [11], Table 1.

Analysis of these data reveals three main types of territories. The territories of the first type, highlighted red in the Table, are characterized by irradiance of 1,250–3,500 MJ/m^2. The territories of the second type include those that are highlighted orange in the Table with irradiance of 4,000–5,400 MJ/m^2. The territories of the third type are those that are highlighted yellow with the highest values of irradiance of 5,400–8,050 MJ/m^2.

The obtained results prove that the whole territory of the Middle East is suitable for the development of solar energy supply, though it is preferable to use the territories belonging to the second and third type as the most helio-capable.

It should be noted that in the autumn-winter period (from November to February) the territory of Syria, Iraq, Iran, and Turkey belong to the first type of illuminance. The United Arab Emirates and Saudi Arabia have illuminance of the second and third type throughout the whole year.

To assess the helio-technical capabilities of regions, it is important to have not quantitative characteristics of irradiance flows, but rather the necessary information about irradiance, that is, about the possibilities of the long-term use of the energy flow in helio-technical machines. That's why the period, during which there is enough sunshine for the effective work of a solar system, is an important characteristic. A significant difference is observed at the beginning and at the end of the year and in the morning and evening hours of a day. That is, the helio-technical capacities of a number of regions in the Middle East decrease considerably.

Table 1

Characteristic of solar radiation for different regions of the Middle East countries

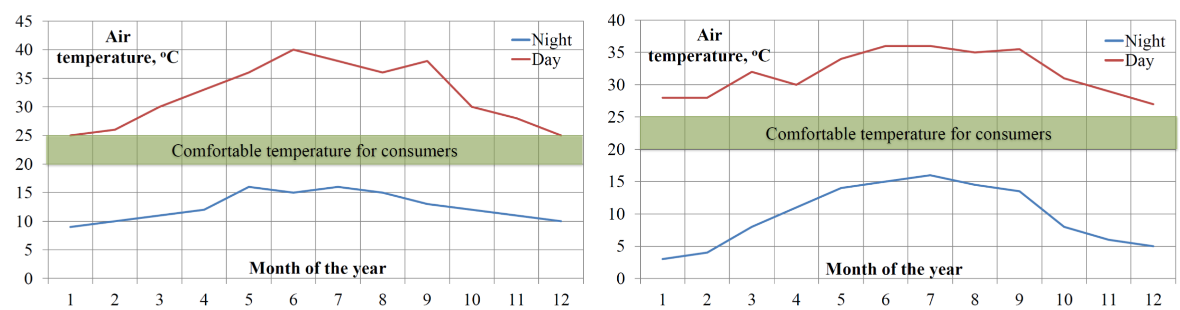
	Syria		United Arab Emirates		Saudi Arabia		Iraq		Turkey		Iran	
Region / month	Der-Ezzor	Damask	Abu-Dhabi	Fujairah	Riyadh	Abha	Erbil	Baghdad	Ankara	Istanbul	Teheran	Mashhad
1	2.48	3.10	4.30	3.89	3.50	4.74	2.43	3.00	1.86	1.47	2.44	2.33
2	3.40	3.50	5.00	4.84	4.60	4.60	3.21	3.80	2.57	2.23	3.33	3.03
3	4.46	4.60	6.70	5.40	5.10	5.37	4.41	4.80	3.80	3.49	4.08	3.58
4	5.58	5.80	6.70	6.54	5.50	5.62	5.41	5.70	4.51	4.83	5.42	4.42
5	6.84	7.40	7.60	7.49	5.60	5.89	6.64	6.50	5.75	6.35	6.42	6.50
6	8.05	8.00	7.60	7.67	6.10	6.01	7.67	7.30	6.59	7.27	7.64	7.81
7	7.84	7.90	7.00	7.03	6.10	5.52	7.37	7.20	6.89	7.41	7.50	7.64
8	6.94	7.20	6.70	6.60	5.90	5.30	6.69	6.60	6.08	6.33	6.92	7.14
9	5.63	6.10	6.50	6.37	5.70	5.73	5.62	5.70	4.91	4.86	5.75	5.72
10	3.82	4.50	5.70	5.57	5.30	6.02	3.90	4.40	3.35	2.89	4.25	4.11
11	2.53	3.00	4.80	4.51	4.50	5.50	2.77	3.30	2.13	1.75	2.92	2.86
12	2.08	2.30	4.60	3.72	3.60	4.81	2.18	2.70	1.53	1.25	1.53	2.17

In addition to the solar radiation, a very important factor for the operation of helio-plants is thermal inertia of a solar system, that is, the time of warming up a helio-plant up to the operating temperature. Thermal power of an electrical solar station must meet the needs of a particular customer within 24 hours in different seasons of the year.

Selective analysis of the temperature climatic conditions in Turkey, Saudi Arabia, and the United Arab Emirates, performed based on the information portal data [11] is shown in Fig. 1–3. The data on mean day and night temperatures during the year in two regions of the specified countries compared to the comfortable temperature in a house are presented graphically.

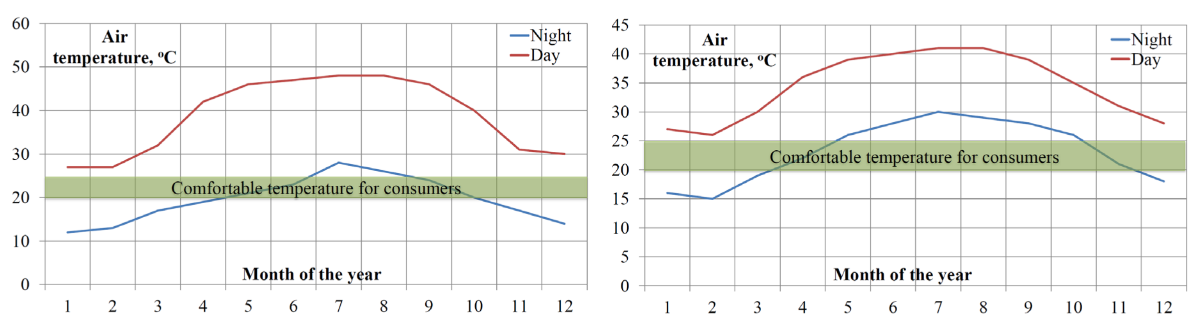
In Saudi Arabia (Fig. 1), daytime temperatures within a year are higher than the comfortable temperature (20…23 °C), which requires air conditioning of premises. During night hours in the period from May to September, the outdoor temperatures are close to comfortable, heating is required to ensure comfortable existence during the rest of the periods.

In the United Arab Emirates (Fig. 2), from March to October, daytime temperatures are higher than comfortable, from November to February; they are equal to comfortable in all regions. Night temperatures throughout the year are in the limits of comfortable. For consumers, air conditioning in the daytime is enough.



a *b*

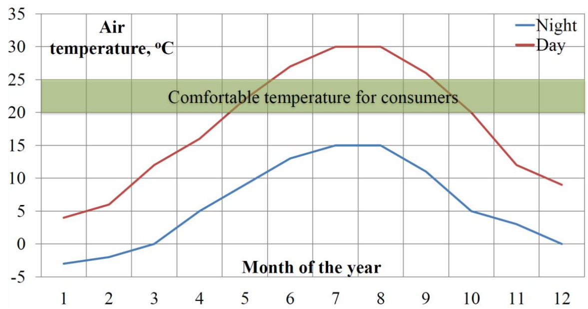
Fig. 1. Average monthly air temperatures in Saudi Arabia: *a* – region of Abha, *b* – region of Riyadh



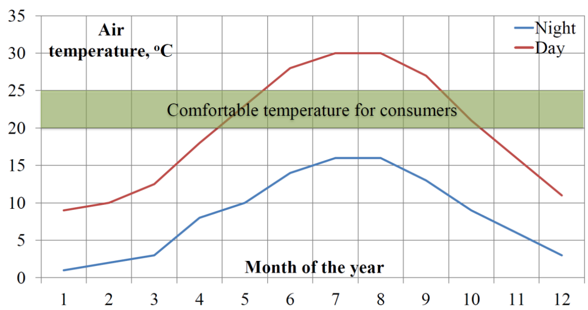
a *b*

Fig. 2. Average monthly air temperatures in the United Arab Emirates: *a* – Abu-Dhabi region, *b* – Fujairah region

In Turkey (Fig. 3), only from June to September, daytime temperatures exceed comfortable values, but maximum temperatures reach only 30 °C. During the rest of the seasons and during nighttime, the temperatures are below comfortable. Under such conditions, heating becomes necessary for consumers.



a



b

Fig. 3. Average monthly air temperatures in Turkey: *a* — Istanbul region, *b* — Ankara region

Similar conclusions were made for all countries; as a result, it is reasonable to create solar houses with the trigeneration system based on small solar power stations.

5. The generalized technological scheme of a small trigeneration system;

The trigeneration system is based on an autonomous photovoltaic solar station of small power, in which the operation mode is rationally selected through coordination of the operation of all elements of the system taking into consideration the changes of seasonal and daily ambient temperatures over the year.

The cold for air conditioning is consumed from a refrigerating machine. The terms are determined by the temperature of the environment, which is higher than comfortable in a particular room. Hot seasons and daytime hours in different seasons are considered the periods of consumption (Fig. 1–3).

The heat for heating is consumed from the same refrigerating machine that operates in a heat pump mode. The terms are determined by ambient temperature, which is lower than comfortable in a particular room. Cold seasons and cold night hours in different seasons are considered the periods of consumption. The system of heat and cold supply from one refrigerating machine is widely known [12], but is limited in use [13].

One of the most effective sites for application of cooling or heat pump technology is the systems of ventilation of public and residential buildings. At a small temperature difference of the incoming and exhaust air, the high energy efficiency of refrigerating machines is achieved under moderate temperatures of ambient air. If the temperatures of ambient air differ greatly from indoor temperatures, the heat and cold supply becomes less effective. Due to this, the introduction of heat regeneration between the flows of exhaust air from the premises and the air that comes from the outside is very promising [14].

The modes of heat and cold supply of residential premises depend on a number of factors [15]: the type of a building, the character of the engineering systems of a building, existing sources of heat or cold, materials of enclosures.

Each of the above factors affects the quantitative and qualitative indicators of consumed heat or cold and the ratio between the types of the thermal load of consumers.

In private houses, additional solar collectors, included to a solar station, are used for the production of hot water, and the existence of a heater-accumulator allow avoiding the negative consequences of peak loads for the preparation of hot water in the morning and in the evening. If a building has an outdoor pool, it is possible to increase a heat share for its maintenance due to an increase in the number of modules and solar collectors [15]. Based on the performed analysis, we carry out a synthesis of the generalized technological scheme of the "solar house" trigeneration (Fig. 4).

The processes of heating or cooling the premises, according to Fig. 4, are performed by a one-stage vapour compressor refrigerating machine driven by an electric motor and consisting of four main elements: a compressor, a condenser, an air chiller (an evaporator) and the throttle body.

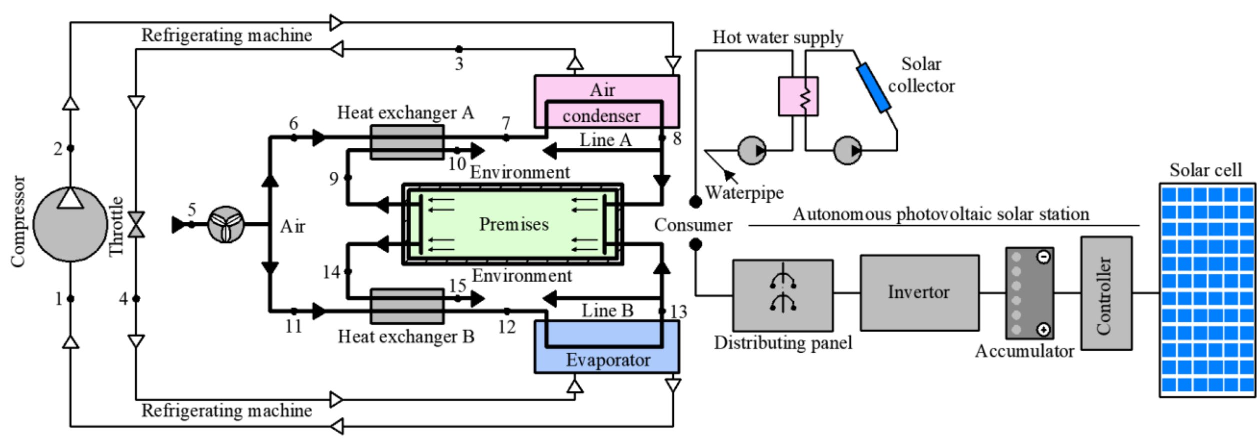


Fig. 4. Generalized technological scheme of a small trigeneration system

Operating modes for the implementation of air conditioning or heating vary, depending on ambient temperature by the automatic adjustment of the determined parameters of the working fluid. An air condenser and an air chiller (an evaporator) perform their functions independently on the modes. The temperature mode in premises is maintained by the fresh air flow from the system of active ventilation, chilled or heated in the heat exchangers of the machine.

A fresh air flow (point 5) is fed by the fan in two directions: to the condenser (point 6) and the evaporator (point 11) of the refrigerating machine.

In the conditioning mode, the flow of chilled air after the heat exchanger *B* (point 12) and the evaporator (point 13) is fed to premises through the incoming line of ventilation. The heated air comes out of the premises (point 14) through the exhaust line. After the heat exchanger *B* (point 15), the air enters the environment.

In the heating mode, the flow of the heated air after the heat exchanger *A* (point 7) and the condenser (point 8) goes to the premises, heats it, and goes out (point 9). The air returns in the environment through the heat exchanger *A* (point 10).

In both modes, the flows that are not involved in reaching beneficial effects in the premises (cooling or heating), according to the technological scheme 1, moving in transit through the corresponding exchangers, operate in the cycle of the refrigerating machine and return to the environment through line *A* and line *B*. The technological scheme supplies the fresh air into the room. Cooling equipment is located outside the premises, placed a single unit in the casing for the protection against external influence. It is possible to select additional equipment for the individual adjustment of parameters of the system of an entire building in the all-year-round cycle.

6. The toolset for determining thermal loads and temperature modes in premises and the elements of the trigeneration system

Interaction of energy flows are shown in Fig. 5, 6 in the coordinate system "Temperature – thermal flow".

6. 1. Energy flows in the block "premises – refrigerating machine"

Thermodynamic analysis of the operating modes in heat exchangers is presented using a particular example. For the analysis, mean statistical data on the temperature climatic conditions of the Middle East countries were used. Mean temperature heads in the units were accepted in accordance with the theory of heat transfer in refrigeration and heat pump equipment.

The temperatures in the nodal points of the technological scheme are given in Table 2.

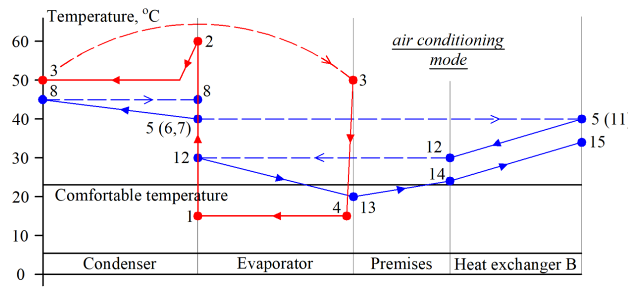


Fig. 5. Energy flows in the system "premises – refrigerating machine" in the air conditioning mode

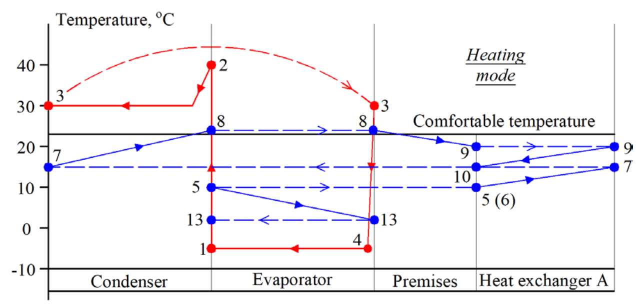


Fig. 6. Energy flows in the system "premises – refrigerating machine" in the heating mode

Table 2

Temperatures at nodal points of the scheme

Point	Name of parameter	Temperature mode of conditioning, T, °C	Temperature mode of heating T, °C
	Working fluid of refrigerating machine		
1	Temperature at suction into compressor	15	–5
2	Temperature at discharge of compressor	–	–
3	Condensation temperature of working fluid	50	30
4	Evaporation temperature of working fluid	15	–5
	Ventilation air		
5	Temperature of ambient air	40	10
6	Temperature at the inlet of heat exchanger A	40	10
7	Temperature at the inlet of condenser	40	15
8	Temperature at the outlet of condenser	45	24
9	Temperature at the outlet of premises	–	20
10	Temperature at the outlet of heat exchanger A	–	15
11	Temperature at the inlet of heat exchanger B	40	–
12	Temperature at the inlet of evaporator	30	–
13	Temperature at the outlet of evaporator	20	2
14	Temperature at the outlet of premises	24	–
15	Temperature at the outlet of heat exchanger B	34	–
	Comfortable temperature in *premises*	23	23

An analysis of Fig. 6 makes it possible to argue on that disposal of heat into air that comes out of the premises should be considered as the main source of reduction of operational costs of thermal processing of the external incoming air in systems of heating and air conditioning of premises.

6. 2. Energy resources in a solar energy station

It is necessary to determine the load and consumed energy to calculate a photovoltaic plant for a house. To determine the electricity consumption, it is necessary to have certificates, containing the information about all sources of electricity consumption, mainly for basic household appliances. Energy consumption should be optimized.

In the considered system, the costs of air conditioning and heating of the premises are separately taken into consideration. Energy balance of household power consumption can be represented in the form of mathematical equation

$$W_{sfs} = \sum W_i \tau_i + W_{ch} + W_{fan}, \qquad (1)$$

where W_{sfs} is the energy power of a solar photovoltaic station; W_i is the energy power of each consumer in a building; τ_i is the term of operation during 24 hours, h/day; W_{ch} is the energy power of a refrigerating machine; W_{fan} is the energy power of a fan.

The most common modules (from monocrystalline silicon) have the unity power w_1=100...120 W/м^2. Therefore, the area of F_{sfs} occupied by the station to provide for household needs is

$$F_{sfs} = W_{sfs} / w_1. \qquad (2)$$

Solar cells are located as agreed with a consumer.

6. 3. Energy flows in residential premises

For the air conditioning mode, external heat flows from solar radiation Q_{sr} through the outer enclosure of the premises Q_{enc} from people Q_{pl} from electric appliances Q_{el} are taken into consideration. Total energy flow Q_{tot}^{cond} is

$$Q_{tot}^{cond} = Q_{sr} + Q_{enc} + Q_{pl} + Q_{el}. \qquad (3)$$

For the mode of heating in residential buildings, heat losses of premises consist of heat losses Q_{enc} through a variety of enclosures, for heating the air Q_{in} that is infiltrated through small gaps in the protective structures of the given premises. All household electrical appliances, lighting and other possible heat sources, general estimated heat losses Q_{tot}^{heat} in the premises are taken into account as heat inflows:

$$Q_{tot}^{heat} = Q_{enc} + Q_{in} - Q_{el}. \qquad (4)$$

6. 4. Energy balances of elements of trigeneration system

In the air conditioning mode:

– energy balance of premises:

$$Q_{tot}^{cond} = M_1 c_{air} (T_{14} - T_{13}); \qquad (5)$$

– energy balance of the air chiller:

$$Q_o^{cond} = M_{wfc} q_o = M_2 c_{air} (T_{12} - T_{13}); \qquad (6)$$

– energy balance of the condenser:

$$Q_c^{cond} = M_{wfc} q_c = M_3 c_{air} (T_8 - T_7); \qquad (7)$$

– theoretical volumetric productivity of the compressor:

$$V_h^{cond} = Q_v^{cond} / \lambda q \,, \qquad (8)$$

– volumetric air consumption through the fan:

$$V_{air}^{cond} = (M_2 + M_3) / \rho_{air}. \qquad (9)$$

In the heating mode:

– energy balance of the premises:

$$Q_{tot}^{heat} = M_1 c_{air} (T_8 - T_9); \qquad (10)$$

– energy balance of the condenser:

$$Q_c^{heat} = M_{wfo} q_c = M_3 c_{air} (T_8 - T_7); \qquad (11)$$

– energy balance of the air chiller:

$$Q_o^{heat} = M_{wfo} q_o = M_2 c_{air} (T_5 - T_{13}); \qquad (12)$$

– theoretical volumetric productivity of the compressor:

$$V_h^{heat} = Q_o^{heat} / \lambda q_v, \qquad (13)$$

– volumetric air consumption through the fan:

$$V_{air}^{heat} = (M_2 + M_3) / \rho_{air}. \qquad (14)$$

Equations (5)–(14) have the following designations*:* M_1, M_2, M_3 are the mass consumptions of the air through the premises, the evaporator and the condenser, respectively; M_{wfo}, M_{wfc} are the mass consumptions of working fluid through the evaporator and the condenser, respectively; q_o, q_c, q_v are the specific characteristics of the cycle of the refrigerating machine; λ is the coefficient of feeding the compressor; c_{air}, ρ_{air} are thermal capacity and air density.

Characteristics of the elements of the trigeneration system are calculated from the relevant equations involving mathematical dependences of the corresponding sections of papers [16, 17]. To select the refrigeration equipment, it is necessary to follow the recommendations: to choose higher values out of the two calculation values V_h^{heat} and V_h^{cond}, V_{air}^{cond} and V_{air}^{heat}.

7. Discussion of results of synthesizing the generalized technological scheme of the trigeneration system for a "solar house"

When synthesizing a technological scheme of the trigeneration system, which is derived from the obtained results (Fig. 4), the creation of a solar house is based on the existence of an autonomous solar photovoltaic station. The climatic conditions of the territory, on which the construction is to start, should ensure permanent year-round production and consumption of cold and heat. For residential premises, it implies air conditioning and heating. Such conditions are inherent for the countries of the Middle East: intense solar radiation throughout the whole year, the existing ambient temperature in different seasons and significant temperature fluctuations in daytime and night time. Climatic conditions are combined with the political-economic indicators of the countries, the problems of centralized power supply and new energy projects of large photovoltaic power stations.

The location of the entire equipment outside the residential premises simplifies maintenance and increases the possibilities of upgrading the system, ensuring environmental cleanliness in a room, improvement of social conditions of the life of people.

The study can be referred to strategic projects and is regarded by the authors as the initial stage in the creation of “solar houses” of the new generation. Most “solar houses” have only the system of heating and hot water supply. This situation limits the study because there is no proof of the rationality of the proposed technical solution. Obtaining two useful effects in a single machine prevented the authors from evaluating the thermodynamic perfection of the system with the help of existing methods. It is necessary to continue the research with the involvement of the thermo-economical approaches.

8. Conclusions

1. As a result of research, it was found that the climate of the Middle East countries completely meets the conditions for the creation of a “solar house”. The integrated trigeneration system based on an autonomous solar photovoltaic station can provide the residents of a solar house with electricity, air conditioning and heating of premises, depending on the seasonal and daily fluctuations of ambient air temperature throughout the whole year.

2. The specific features of the generalized technological schem**e** are that it contains one single-stage refrigerating machine and the system of active ventilation, refrigeration equipment located outside the residential premises.

The temperature mode in the room is maintained by the fresh air flow from the system of active ventilation, cooled or heated in heat exchangers of the machine. Thanks to this scheme, the system maintenance is simplified, maintenance costs for thermal processing of the external incoming air decrease and ecological cleanliness of the residential premises is ensured.

3. The research makes it possible to argue on that a “Solar house” with the trigeneration system based on an autonomous solar photovoltaic station is a new scientific and technical solution for the implementation of the idea of meeting energy, social and environmental needs of people in the Middle East regions.

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