

## Increasing the Efficiency of the Solar Plant for Desalination of Water

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### ABSTRACT

The article is devoted to the improvement of the design of a desalination solar plant for more efficient and economical production of desalinated water due to intensive evaporation of the boiling solution, reduction of energy losses to the external environment and the absence of the need for continuous adjustment of the direction of the light-receiving part of the solar plant. The expedient parameters of the angles of inclination of the optical axis of the lens relative to the azimuth and the incidence vector of solar radiation, which ensure high performance of the solar plant, were experimentally substantiated. The use of a solar collector equipped with an additional heat accumulator will allow water to be supplied for desalination at a temperature of more than 50 °C in sunny weather, and at a temperature of 33–36 °C in variable cloudiness, which will help to increase the efficiency of the desalination solar plant. The presence of a heat accumulator and a layer of thermal insulation under cloudy conditions allows maintaining the operating water temperature at 33–36 °C 4.4 times longer than without them.

**Keywords:** solar plant, water desalination, solar collector, converging lens.

### INTRODUCTION

Global environmental problems of our time, such as climate change, population growth and, as a result, unequal distribution of natural resources, are the consequences of the global freshwater deficit, which today is less than 3% of all water resources on the planet (Gude, 2017.) Due to the loss of ice caps at the poles as well as man-made pollution and disturbance of mainland water bodies, the freshwater reserves are rapidly decreasing, and if the current dynamics continue, these processes can lead to catastrophic consequences. In addition to reducing the impact of these negative factors as soon as possible and applying modern technologies to improve water quality (Kostenko et al., 2022; Tavrel et al., 2022), an effective solution to

the current situation is the widespread use of desalination technologies (Maftouh et al., 2023).

Desalination is the process of removing salts and other unnecessary minerals from water, which subsequently makes it suitable for drinking and use in economic activities. Desalination is a very energy-intensive process, and the profitability of the technology is primarily influenced by the type and amount of energy required to produce fresh water. Depending on the technology, desalination can use electrical and thermal energy, or a combination of both (Mohammadi et al., 2019). In general, the existing desalination methods are divided into two general types: membrane technologies and thermal desalination.

Membrane technologies in many countries today are considered to be the most promising

methods of desalination of mineralised water primarily due to the high efficiency of such technologies (Ahmed et al., 2019). Among the membrane desalination technologies, the most popular in the world are reverse osmosis, electrodialysis, direct osmosis and membrane distillation (Alkudhiri et al., 2012). The significant advantages of such technologies, in addition to efficiency, are relatively low operating temperatures compared to thermal methods. At the same time, the need for regular maintenance of membrane performance, high energy consumption to create the required pressure, and the complexity of membrane-type desalination plants hinder their distribution in the global desalination equipment market (Amy et al., 2017).

Today, thermal desalination methods continue to play a significant role in the preparation of fresh water, based on the process of separating distillate from salt water through the use of thermal energy (Ahmed et al., 2019). At the same time, desalination technologies are increasingly relying on renewable energy sources, such as solar (Pugsley et al., 2016), wind (Srithar et al., 2018), geothermal energy (Shelare et al., 2023; Kostenko et al., 2018), as well as energy from hydroelectric power plants (Reif et al., 2015) and energy from biological raw materials. The main types of thermal desalination technologies are multistage instantaneous evaporation, multistage distillation etc.

As it was already mentioned, one of the main obstacles to the large-scale implementation of salt water desalination technologies is the need for a large amount of energy to ensure the desalination process and, primarily for membrane methods, rather complex equipment that requires careful operation, regular inspections and maintenance by qualified personnel (Khawaji et al., 2008). In conventional desalination systems, energy is usually obtained by burning non-renewable fossil fuels (Sharshir et al., 2016; Shukla et al., 2017). However, the current global decarbonisation policy is significantly shifting the emphasis to the use of alternative energy sources for desalination of saline water, thereby solving several environmental problems at once (Eke et al., 2020).

Desalination methods using solar thermal energy, which usually does not require additional conversion, are the most widely used, and they use relatively easy-to-learn and easy-to-operate energy concentration and utilisation technologies (Park et al., 2016). Modern solar desalination

systems mostly use photovoltaic solar energy and direct solar thermal heating. That is why compact solar distillers are becoming increasingly widespread compared to other desalination methods (Peng et al., 2021).

The principle of operation of such plants is based on the use of direct solar radiation, which evaporates the distillate, separating it from the salty residue (Manokar et al., 2014). The general design of a solar distiller includes a hermetically sealed tank with a transparent lid that transmits solar radiation. The evaporated water rises from the tank under the influence of thermal energy and is retained, condensing on the inner surface of the lid, and then the treated water is collected in a separate container (Maftouh et al., 2023). The main disadvantage of this technology is the low productivity of such a solar plant (Sakthivadivel et al., 2021), which is primarily due to the low temperature of water heating in the ‘solar pond’ that is lower than the boiling point of the solution, and the significant energy consumption for its heating in Peltier modules (Mykytyuk et al., 2015).

This is due to the fact that the temperature performance and heat transfer of solar distillers depends on a number of climatic factors, such as:

- solar radiation activity in a particular region (Srithar et al., 2018) the degree of atmospheric transparency, and the presence or absence of wind;
- design parameters of the plant and physical parameters of water: transparency of fresh water in the upper layer of the pond; concentration of mineral impurities in different layers of the water bath;
- heating surface area;
- quality of thermal insulation on the bottom and side walls of the plant; thickness of the transparent lid (Panchal et al., 2011);
- depth of the water bath in the tank;
- availability of concentration equipment that directs sunlight into the pond, etc.

The activity of solar radiation, or radiation intensity, is one of the main factors affecting the efficiency of a solar distiller. The maximum energy storage performance of the solar desalination plant is observed at noon, i.e. the time when the highest intensity of solar radiation is observed (Srithar et al., 2018).

The key factors are the reaction surface area and the total depth of the collector bath. The area

of influence or active area of the desalination plant depends on the evaporation rate. Thus, the evaporation rate increases along with the area of the solar distiller's water bath. The evaporation rate is also affected by the depth of the collector bath: a greater depth slows down the process of heating and evaporation of the liquid (Badran, 2007) thereby reducing the overall efficiency of solar distillers of this design.

The efficiency of solar distillers is influenced by the use of nanofluids, which have increased thermal conductivity, intensifying the absorption of solar thermal energy and, as a result, accelerating evaporation. Experimental studies show that the use of such nanofluids in solar distillers integrated with an external condenser can increase the efficiency of the plants by 16%, compared to typical liquid (Kabeel et al., 2014). The heat transfer rate is also significantly affected by the thickness of the glass cover (Nwosu et al., 2023), as it is the main conductor of solar radiation in the desalination plant. The results of experimental studies (Felicia et al., 2022) show that a glass cover thickness of 3 mm provides a maximum efficiency of 15.5%, with further increases in thickness significantly reducing the performance of the plant. The process of heat transfer between the glass and the atmosphere is carried out by convection and depends on the wind speed. Increasing the wind speed allows obtaining more distillate, accelerating condensation (Selvaraj et al., 2018).

Another crucial disadvantage of the known solar water desalination systems is the need to adjust the light-receiving part daily in the direction of the solar orbit. This, in addition to requiring constant monitoring of the plant's operation, also significantly affects its performance (Ayoub et al., 2012).

Clouds, fog, dust, etc. negatively affect the performance of solar plants. This disadvantage is partially levelled out when obtaining heated water using an additional heat accumulator (Kostenko et al., 2020). A genetic disadvantage of using solar plants is the limitation of productive work time by the duration of daylight hours, which makes it necessary to ensure maximum energy extraction during this period. The need to ensure the maximum efficiency of solar plants during the relatively short period of their exposure to the Sun is a very urgent technical problem.

Optimisation of these factors in modern solar distillation desalination plants will allow for effective mass use of this ergonomic technology in the future, which will help to alleviate the issue of fresh water shortage on the planet.

The purpose of the paper was to intensify the production of distillate by improving the design of a desalination solar plant.

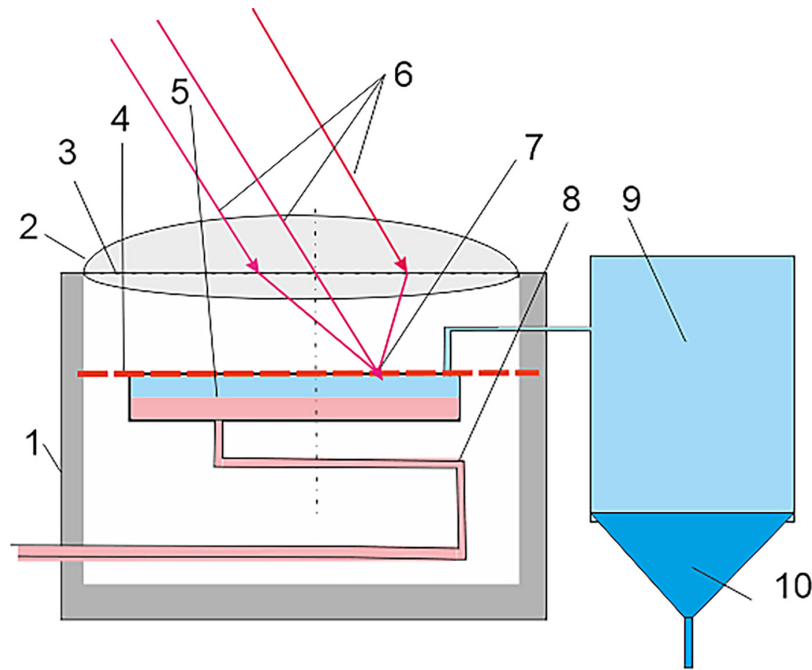
## MATERIAL AND METHODS

The idea of the chosen method of desalination of salt waters is to ensure continuous concentration of solar energy on the vapour-forming structure and to deposit excess heat on additional elements. For desalination of salt water, it is proposed to improve the design of the solar plant by installing a light-receiving part in the form of a converging lens on the device body. The lens, which has a main optical plane and a focal surface, acts as a lid, and forms a hermetically sealed volume with the body, which is filled with a gas with a high heat content, such as helium. A hollow heat sink is mounted in the body of the device, with the upper surface of the heat sink rigidly fixed in the focal surface of the converging lens (Fig. 1). The heat sink void is filled with primary water, or more precisely, a salt solution to be evaporated.

Placing the converging lens on the top of the body allows concentrating the sun rays in the limited space of the lens focus, where the temperature is several times higher than the boiling point of water. The temperature generated in the lens focus depends primarily on the aperture, i.e. the diameter of the light flux at the entrance to the lens. Due to the fact that the side focuses of the lens, which exist at any position of the Sun at any time of daylight and season, will be located in a geometric place, the focal surface of the lens, there is no need to continuously adjust the position of the light receivers of the solar plant.

Installation of the upper surface of the heat exchanger in the focal surface of the lens determines that the area of this surface is subjected to high-temperature heating, and it heats the entire body of the heat exchanger as well as the solution in it. The advantage of the proposed design of the solar plant is also that in this case, the solution in the heat receiver can be heated to the boiling point of water, which allows for a qualitative acceleration of the process of water vapour formation not only due to evaporation from the surface of the heated liquid, but also mainly due to its intense boiling.

It is proposed to manufacture the solar plant body with additional thermal insulation, such as foam, which reduces heat energy losses to



**Figure 1.** Scheme of a solar water desalination plant: 1 – insulated gas-filled body; 2 – converging lens; 3 – main optical plane of the lens; 4 – focal surface of the lens; 5 – heat sink; 6 – sunlight flux; 7 – side focus of the lens; 8 – solution supply pipeline; 9 – water vapour condenser; 10 – water collection cavity

the environment. Filling the hermetically sealed volume of the body with a gas characterized by a high heat capacity ensures that this gas accumulates excess heat in bright sunlight. A pipeline for supplying the solution to the heat receiver is placed in the body of the solar plant filled with gas with a high heat capacity. The pipeline preheats the liquid by several degrees, which increases the inlet temperature of the evaporating solution and increases the efficiency of the solar plant, especially in variable cloudiness, during periods when there are no direct rays of the Sun. The water vapour generated in the heat exchanger enters the condenser, where it becomes liquefied and flows into the freshwater collection cavity.

The use of the proposed solar plant to produce fresh water from solutions allows for more efficient and economical desalination of salt water using solar thermal energy by ensuring intensive boiling of the solution, reducing energy losses to the environment, and eliminating the need for continuous adjustment of the solar plant direction.

The performance of a distillation desalination plant significantly depends on the illumination of the lens receiving the light, the length of daylight hours, the angle of incidence of the sun rays and the overall solar activity. At any position of the Sun, its rays hit the lens and focus on the heat sink, however, if the angle of misalignment

between the optical axis of the lens and the sun ray vector is significant, the linear aperture of the lens, i.e. the amount of energy that reaches the lens surface, may be significantly reduced. Due to the likelihood of such a complication, an experimental assessment of the effect of the misalignment angle on desalination efficiency was carried out. The directions of illumination and angles of incidence of solar radiation, as well as temperature changes in the Donetsk region of Ukraine (geographical point  $48^{\circ}26'51''$  N and  $38^{\circ}19'39''$  E) were studied.

The direction of solar radiation was studied using an experimental gnomon (with a working part height of 30 cm) and hourly measurements of the direction and length of the shadow from it during the daylight hours. The measurements were conducted in July, with a sunny day of 11 hours (from 7:00 to 18:00) and an average air temperature of  $24\text{--}35^{\circ}\text{C}$ . The location of the experimental gnomon at the work site and the process of measuring the azimuth relative to the south and the vertical angle of solar radiation are shown in Figure 2.

In accordance with the established length of the gnomon shadow, the angles of incidence of solar radiation at the experimental site at different hours of daylight hours were obtained. The averaged data of the incidence angle and direction of solar radiation are shown in Table 1.



**Figure 2.** Position of the shadow of a gnomon with a height of 30 cm during daylight hours, the numbers indicate the hours

When analysing the results obtained, it should be noted that the vertical and horizontal angles of surface irradiation during daylight hours vary in a fairly wide range. In the horizontal plane, the direction of the shadow from the gnomon changed by  $181^\circ$  (from  $126^\circ$  to  $-55^\circ$ ), and in the vertical plane by  $39^\circ$  (from  $19^\circ$  to  $58^\circ$ ).

This means that the input aperture of the device can vary significantly due to the large angle of inconsistency in the morning and evening relative to the middle of the day. The optimum location in the lens space is such that the solar energy is maximised. The design of the desalination plant allows limiting oneself to roughly aiming the main axis of the lens three times a day, e.g., in the morning, azimuth  $90^\circ$ , vertical angle  $35.40^\circ$ ; in the middle of the day, azimuth  $40\text{--}70^\circ$ , vertical angle  $53\text{--}58^\circ$ ; in the evening,  $0^\circ$  and  $35\text{--}40^\circ$ , respectively. In intermediate positions of the Sun, due to the design properties of the plant, a relatively high level of solar energy extraction is provided. It should be noted that when the Sun is low above the horizon, the intensity of infrared radiation decreases, the rays pass through a larger layer of the atmosphere, so a compromise is needed between complicating

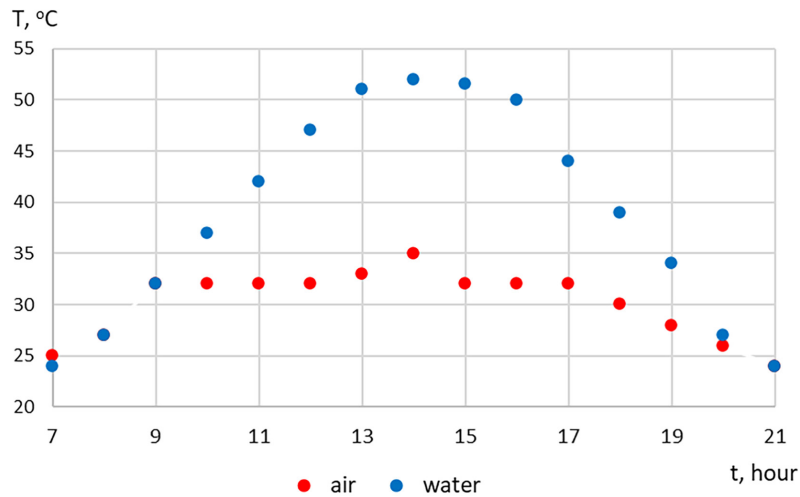
the orientation of the plant or ignoring the correction with a slight loss of energy.

Also, the general climatic indicators of solar radiation and their possible impact on the efficiency of the distillation desalination plant were assessed at the experimental site. For this purpose, a mock-up collector-type solar plant was built, in which measurements of the water temperature at the inlet to and outlet from the mock-up were made using electronic temperature sensors. At the same time, the air temperature, and the flow rate of the coolant, i.e. tap water, were measured. The initial temperature of the water entering the device was  $24^\circ\text{C}$ , and the water flow rate was  $0.2\text{ L/min}$ .

At the beginning of the experiment at 7:00, when the air temperature was  $25^\circ\text{C}$ , the water temperature at the outlet of the collector was  $24^\circ\text{C}$ , i.e., no heating process took place. From 10:00 to 17:00, the air temperature was  $32\text{--}34^\circ\text{C}$ , and the water temperature at the outlet of the system was  $37\text{--}52^\circ\text{C}$ . The maximum level of water heating,  $52^\circ\text{C}$ , was recorded between 13:00 and 15:00. Figure 3 shows a graph of the temperature of water at the outlet of the collector and air during the day.

**Table 1.** Indicators of the angle of incidence and direction of solar radiation

Hour	Length of shadow from the gnomon, cm	Azimuth relative to the south, deg.	Angle of incidence of rays, deg.
7:00	86	126	19.23
08:00	64	111	25.11
09:00	44	98	34.29
10:00	30	86	45
11:00	22	74	53.75
12:00	19	63	57.65
13:00	18.5	52	58.34
14:00	21.5	37	54.37
15:00	28.5	20	46.47
16:00	37	0	39
17:00	52	-29	29.98
18:00	86	-55	19.23



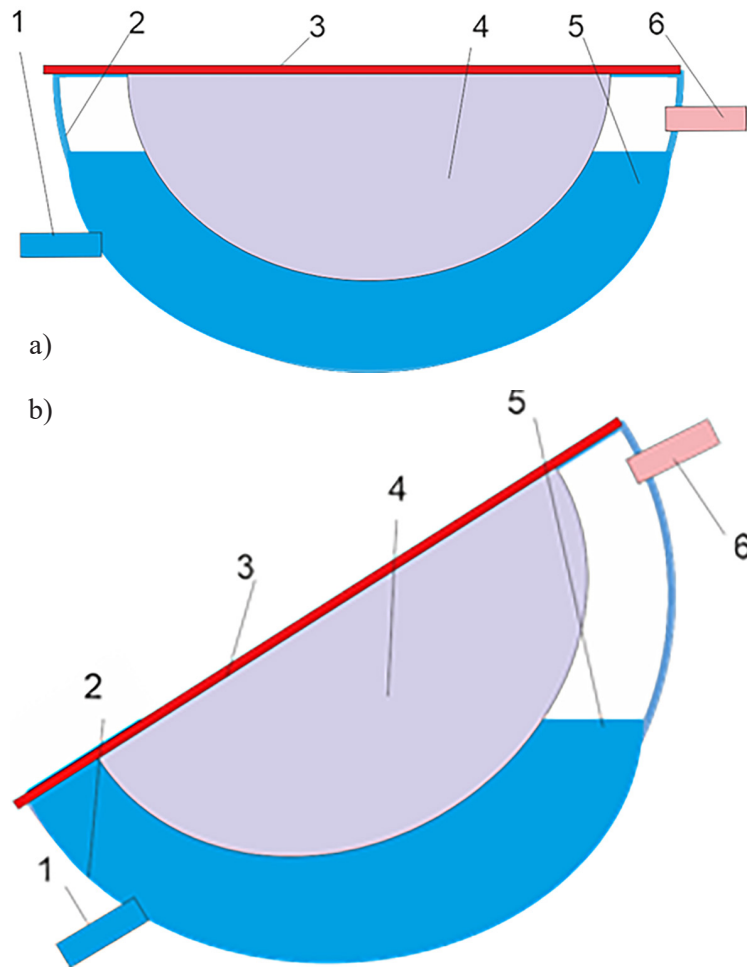
**Figure 3.** Temperature dynamics ( $T$ , °C) of the coolant at the outlet of the solar collector and air during daylight hours ( $t$ , h)

The same experiment was conducted under the conditions of variable cloudiness. It was found that at an air temperature of +30 °C, the water temperature at the outlet of the solar collector is +50 °C. When the Sun was blocked by clouds during the first 30 minutes, a 10% decrease in the water temperature at the outlet of the solar plant mock-up was observed; after the next 30 minutes, the efficiency of the plant was 0, since the water heating had completely stopped. Such indicators, in authors’ opinion, can be explained by the presence of a certain thermal resource in the form of heated masses in the structural elements of the plant, which explains the inertia of the water heating process for the first half hour. The conclusion is that in order to level up the effect of cloudiness, it is advisable to increase the mass of bulky elements of the plant supporting the water heating process.

## RESULTS AND DISCUSSION

The conducted studies have confirmed the expediency of taking into account the location of the Sun relative to the focal plane of the lens. When the lens is located horizontally, the sun rays hit the lens surface at an angle for almost the entire part of the daylight hours, which results in a decrease in the lens aperture. Tilting the lens towards the Sun allows increasing the solar energy received by the solar panels installed in its focal plane. The earlier described design (see Fig. 1) does not provide for the location of the heat receiver at an angle, which makes the process of boiling the solution more difficult.

The authors propose the following improvement of the heat sink design (Fig. 4). Its outer body is made in the form of a metal hemisphere



**Figure 4.** Heat sink with horizontal (a) and inclined position (b) 1, 6 – branch pipes for water supply and steam removal, respectively; 2 – outer hemisphere; 3 – disc made of heat-resistant material; 4 – inner hemisphere made of heat-conducting material; 5 – solution to be evaporated

hermetically sealed at the end with a disc of heat-resistant material. The body is connected to the water inlet and steam outlet pipes. The disc is mechanically connected to the lens in such a way that the area of the disc coincides with the focal surface of the lens. A small hemisphere made of a material with high heat capacity and thermal conductivity is attached to the inner surface of the disc. There is a void between the outer and inner hemispheres, which is partially filled with the solution to be evaporated.

The heat exchanger operates as follows. In the horizontal position of the lens (Fig. 4a), the disc of heat-resistant material is constantly in the side focus of the lens, where the temperature can reach more than 1,000 °C. The heat generated in the disc is transferred to the heat-conducting material and dissipates in it. A part of the inner sphere comes into contact with water and transfers thermal energy to it, heats it up and causes it to boil.

When the lens is installed at an angle to the horizon (Fig. 4b), the rigidly connected disc of heat-resistant material remains in the focal plane. Due to the spherical shape of the structure, the contact area of the inner sphere with water remains almost unchanged. The process of water heating and evaporation continues.

In addition to the fact that a solar desalination plant can extract more solar energy with this heat exchanger with a more rational positioning of the lens, it has another advantage. A small hemisphere made of a heat-conducting material has a significant heat capacity. This ensures that a certain amount of thermal energy is stored in the bulk of the hemisphere material. In the event of short-term cloudiness, the Sun stops heating the disc, but evaporation continues due to the accumulated heat.

An important parameter that affects the efficiency of a solar water desalination plant is the

temperature of the water supplied for desalination. The higher the water temperature at the inlet to the desalination plant, the higher the efficiency of the plant. This is because the desalination plant spends less time and solar energy heating the water, and thus the desalination process is accelerated. It is possible to accelerate heating by adding a heating element to the desalination plant. However, the use of conventional heating elements powered by electricity is impractical from economic and environmental points of view. Therefore, the authors propose to combine a solar water desalination system with a solar collector (Fig. 5).

Salt water first enters the solar collector (Kostenko et al., 2020), which has a hermetically sealed body made of two types of materials: the upper part is made of a transparent material, and the inner surface facing the Sun is made of a dark material. Inside the body there are pipes with ducts for the coolant passage, which have an inlet and an outlet on the surface of the solar collector. The collector body is connected by a hinge to the bracket, which, in turn, is also connected by a hinge to a support riser installed on the ground, next to which the heat accumulator is located. The heat accumulator is filled with a substance that has high thermal conductivity and heat capacity. A housing made of insulating material (a layer of foam) is constructed around the solar collector body, where the inner surface of the housing is covered with a light-reflecting layer, and the outer

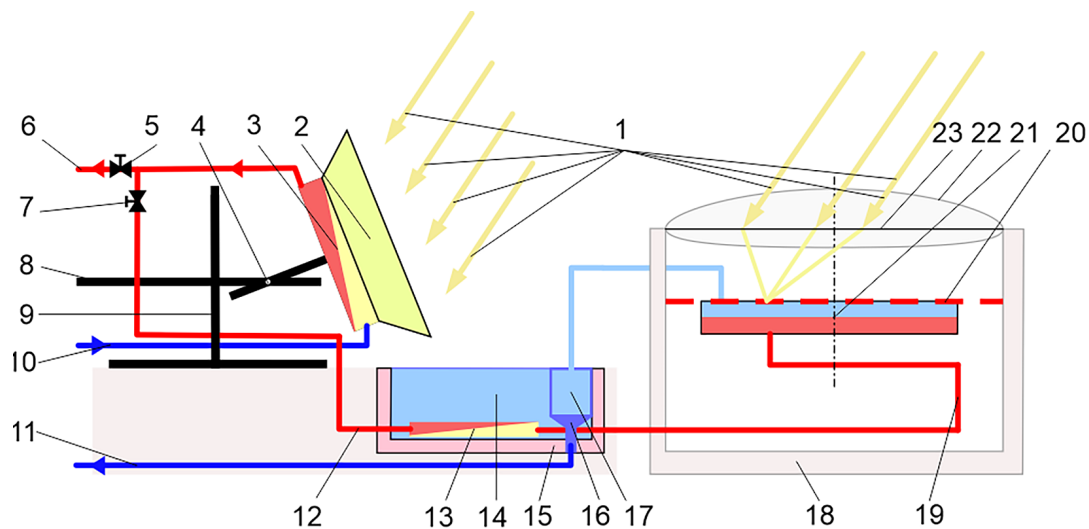
perimeter of the housing has the same size and shape as the perimeter of the heat accumulator.

The peculiarity of such a solar collector is the presence of an additional heat exchanger, which acts as an accumulator for accumulating excess midday solar energy. The presence of an additional heat exchanger reduces the dependence of the solar collector on such a natural factor as cloudiness, and therefore increases the efficiency of the plant after sunset or when the sky is covered by clouds.

Previous field studies conducted by the authors (Kostenko et al., 2021) confirm the high efficiency of this type of solar collector. Thus, under normal operating conditions, at an average air temperature of +30 °C, the water temperature at the outlet of the solar collector is 50 °C. When variable cloudiness appears, a 10% decrease in the water temperature at the outlet of the collector is observed after 100 minutes, and a complete cessation of heating is observed after 4 hours.

These data indicate that the presence of a heat accumulator and a layer of thermal insulation under cloudy conditions allows maintaining the operating water temperature at 33–36 °C 4.4 times longer than without them.

The salt water heated in the solar collector is then piped to the solar plant where it is desalinated. The temperature of the water at the inlet to the solar plant will be 50 °C in normal sunny weather, and 33–36 °C in the case of variable cloudiness.



**Figure 5.** Schematic of a combined solar water heating and desalination plant: 1 – sunlight flux; 2 – housing; 3 – hermetically sealed body; 4 – bracket; 5, 7 – valve; 6, 12, 19 – hot water pipeline; 8 – rail; 9 – rack; 10, 11 – pipelines for cold water and distillate, respectively; 13 – heat exchanger; 14 – heat accumulator; 15, 18 – insulation layer; 16 – cavity for collecting condensed water; 17 – water vapour condenser; 20 – focal surface of the lens; 21 – heat sink; 22 – converging lens; 23 – main optical plane of the lens



The advantage of the proposed design of the desalination plant is that the placement of the water vapour condenser in the water bath of the heat accumulator will not allow the loss of thermal energy released during condensation, but it could be used as an additional source of water heating.

The disadvantages of the proposed system for desalination of salt water include a high probability of corrosion of the solar collector elements. Heating of salt water can provoke the formation of scale on heat transfer surfaces. Therefore, in the future, the possibility of an additional means of protecting the structural elements of the solar collector from corrosion should be considered. To maintain the solar plant operation at a high level in the dark, it is recommended to carry out flushing with solutions that prevent the formation of scale on the pipelines and the heat sink cavity, and to clean the surface of the converging lens.

## CONCLUSIONS

The design of a solar plant for desalination of salt water was proposed, on the body of which a device receiving infrared rays in the form of a converging lens is installed, and the water heater is located in the focal plane of the lens. This design makes it possible to produce desalinated water more efficiently and economically due to intensive evaporation of the boiling solution, reduction of energy losses to the external environment, and the absence of the need for continuous adjustment of the direction of the light receiver of the solar plant.

As a result of the experimental studies, the expedient parameters of the angles of inclination of the optical axis of the lens relative to the azimuth, and the incidence vector of solar radiation which ensure high performance of the solar plant, are experimentally substantiated.

Increasing the mass of the fixed parts of the desalination plant that are heated by infrared rays reduces the negative impact of short-term cloudiness on the steam production process.

To increase the efficiency of the desalination plant using solar thermal energy, it is proposed to initially heat the water in a solar collector equipped with an additional heat accumulator, which will allow water to be supplied for desalination at a temperature of more than 50 °C in sunny weather, and at a temperature of 33–36 °C in variable cloudiness.

The placement of the steam condenser in an additional heat accumulator allows to direct the resource of latent heat of steam condensation to preheat the water entering the desalination plant and increase the efficiency of the fresh water production process.

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