Using Solar Energy for Autonomous Water Supply to Communities

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Abstract. Global water consumption grow steadily. In regions with a shortage of fresh water, its production is accompanied by a significant expenditure of energy, as a rule, it is a burning of hydrocarbon fuels. This factor has a negative impact on the environment. The aim of this work is to develop an energy-efficient “green” technology for the desalination of seawater and the production of fresh water from contaminated sources, through its forced evaporation with subsequent condensation of moisture. The process of obtaining fresh water is due to pre-saturated air in a closed thermodynamic cycle. The paper presents the thermal balance of modular installations. To increase the insolation power per unit area, it is possible to use various centers of solar energy. Experimental studies and a comparison of the performance of two variants of desalination plants in water with each other and with theoretically possible productivity were carried out. The productivity of the technologies is sufficient for the autonomous supply of drinking water to individual settlements and for the cultivation of plant foods by the hydroponic method.

1. Introduction
The shortage of fresh water has become a systemic factor affecting the socio-economic development of territories and regions. Due the population growth the demand for clean water will increase one and a half times according to various forecasts by 2050. As a result, expenses increased not only for household use, but also for irrigation of land for growing food. In the structure of global water use, agriculture occupies two thirds of the volume of water resources used. Also large consumers are energy, housing and communal services and industry.

We need to hear that many surface sources today have a critical level of pollution, and groundwater is over-exploited (in Saudi Arabia groundwater level drops 1.2 km and replenishment will require at least 25 years).

In this regard, there is an increasing need not only to intensify existing methods of treating surface and underground waters, and also into obtaining fresh water use desalination technologies, but in practical implementation of small-sized fresh water production plants operating with limited energy resources. Such small-sized installations can be successfully decentralized to operate in areas remote from the main infrastructure, in areas with no traditional sources of water supply. Use of small-sized installations, including in water transport is actually.
To date scientists around the world have conducted a significant number of studies on alternative methods for producing fresh water, and in particular the improvement of condensation methods for desalination of sea water [1, 2, 3]. However the ubiquity of such technologies is constrained by their relatively low productivity with significant energy costs (about 120 ... 130 kWh/m$^3$ of water and the amount of carbon dioxide released into the atmosphere (29.1 kg/m$^3$) [4].

2. Aim and goals
The use of solar energy in systems of condensation of moisture from the air has considerable potential. If we compare the maps of solar insolation and water deficit, in many cases there is a coincidence of territories (figure 1, 2). The saving of fuel and energy resources and, consequently, the reduction of CO$_2$ emissions due to the introduction of renewable energy sources will make condensation technologies (HDH-technologies) more economical and, ultimately, will solve the problem of water shortages on a local scale. This is true for small households and enterprises located in the coastal marine and oceanic zone.

Thus, the aim of this work is to develop an energy-efficient “green” technology for desalination of sea water and obtaining clean, fresh water from contaminated sources, through its forced evaporation with subsequent condensation of moisture.

Figure 1. Solar insolation map
Goals of research:
- To carry out a theoretical justification of the technology for producing fresh water, working on the principle of forced saturation of air with moisture and its subsequent condensation with use the radiant energy of the sun.
- Development new technical solutions for the implementation of the technology in various conditions of its application, taking into account the existing world experience in the use of condensation technologies and eliminate their shortcomings.
- Conducting comparative experimental studies of the productivity of the technology in taking off pure, fresh water for various technical solutions, depending on the input power and condensation conditions.
- Comparing experimental studies with theoretically possible productivity of freshwater plant.

3. Technology description
The use of modular plants (units) is proposed to obtain condensate. The schematic diagram of the technology is shown in Figure 3. The principle of operation of modular units is based on saturation of atmospheric air with moisture due to the heating of sea water by solar energy and its forced evaporation, followed by the release of moisture in a cold condenser located below sea level [5, 6, 7].

The modular installation for producing freshwater from the air by the method of moisture condensation works in a closed thermodynamic cycle. Air is the working medium for transferring water vapor. The implementation of the closed cycle in the technology eliminates air purification from impurities and simplifies the design of the module.

During the operation of the installation, it is assumed that the heat released during the condensation of moisture from the air is partially recovered in order to pre-heat the seawater entering the evaporator. The heat exchanger-recuperator, in addition to heating the incoming seawater, also acts as a supercharger of seawater into a thermally insulated container (evaporator) due to the density difference between the cold surrounding sea water and the one heated in the recuperator.
The circulation of the vapor-air mixture in the system is carried out by a fan driven by solar photovoltaic batteries. A detailed description of the principle of operation of modular units for desalination of seawater is given in [6, 7].

4. Heat balance of modules

Let’s consider the process of obtaining fresh water (condensate) from the air, using the technology described above. In general, without taking into account the thermal losses of modular units the energy balance has the following form:

\[
E_s = Q_{air} + Q_{water} + Q_{evo},
\]

where \(E_s\) is supplied solar energy, J/sec; \(Q_{air}\) – the heat input for incoming dry air heating, J/sec; \(Q_{evo}\) – absorbed heat during the evaporation of seawater inside the floating buoy tank (1), J/sec; \(Q_{water}\) – the heat input for seawater heating without the use of condensation heat recovery, J/sec.

The supplied solar energy can be determined from equation:

\[
E_s = N \cdot S,
\]

where \(N\) is the solar radiation power, W/m\(^2\); \(S\) is the insolation area, m\(^2\).

In the process of insolation, the temperature potential of the air increases inside the vessel of the plant (1) with transferring the amount of heat \(Q_{air}\):

\[
Q_{air} = c_{air} \cdot M_{wa} \cdot (T_2 - T_1),
\]

where \(T_1\) is the temperature of the cooled air incoming to the tank (1), equal to the temperature of the surrounding sea water, K; \(c_{air}\) – average specific heat of air, J/kg·K, in the range of operating temperatures; \(M_{wa}\) – mass flow rate of incoming air, kg/sec; \(T_2\) is the temperature inside the heat insulated tank (1) in floating buoy, K.

Wet air is considered as a mixture of individual components: dry air and moisture vapor. In this case, the density of moist air can be determined from the partial pressures according to the known expression [8]:

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**Figure 3.** Schematic diagram of the operation of a modular unit for desalination of seawater with an additional heat exchanger-recuperator.
where $\varphi$ is the relative humidity of air in the buoy tank; $\mu_{\text{water}}$ – molar mass of moisture vapor (water), kg/mole; $\mu_{\text{air}}$ – molar mass of air, kg/mole; $R_0$ is the universal gas constant, J/(mole·K); $p_1$ – is the partial pressure of saturated vapor, determined from the dependence [9]:

$$p_1 = \left(1.0016 + \frac{3.15 \cdot p_{\text{atm}}}{10^8} - \frac{7.4}{p_{\text{atm}}}\right) \cdot 611.2 \cdot e^{\frac{17.62 T_2^\circ C}{243.12 T_2}},$$

(5)

where $T_2^\circ C$ is the temperature in the buoy tank in degrees Celsius, $^\circ C$.

Calculation by formulas (4) and (5) showed that in a given range of temperature changes the density of the air-vapor mixture at atmospheric pressure varies insignificantly, therefore, the mass flow of air dried in the condenser and saturated with moisture in the buoy tank (1) during its circulation in closed thermodynamic cycle can be considered identical.

Heat absorbed during evaporation of moisture from the water surface in the buoy tank $Q_{\text{evo}}$, J/sec:

$$Q_{\text{evo}} = c_{\text{evo}} \cdot M_i,$$

(6)

where $c_{\text{evo}}$ is the specific heat of evaporation, Joules/kg; $M_i$ – mass flow of evaporating water, kg/sec.

The energy spent for heating seawater supplied to the evaporator tank, $Q_{\text{water}}$, J/sec:

$$Q_{\text{water}} = c_{\text{water}} \cdot M \cdot (T_2 - T_1),$$

(7)

where $c_{\text{water}}$ is the heat capacity of incoming sea water, J/(kg·K); $M$ is the mass flow rate of seawater entering to the evaporator tank of seawater, kg/sec.

It should be noted that the mass flow of heated water $M$, and the mass flow of water $M_i$, evaporated from the surface of the buoy, are not equal to each other. Their difference, $\Delta M = M - M_i$, is a value constantly circulating in volume of evaporator. The water flow corresponding to $\Delta M$ is intended for the constant renewal of seawater in the volume of evaporator, since during the operation of the unit the total salt content increases with the evaporation of seawater. To avoid this, a regular washing of the evaporator tank with heated seawater with a low salt concentration is necessary.

The amount of moisture carried by air in a closed thermodynamic cycle, per unit of time, should be less than the evaporation intensity of heated water from its surface inside the evaporator tank. The analysis of the many empirical formulas to determine the intensity of water evaporation (kg/m$^2$·sec) with its free surface depending on the temperature and air flow rate showed that in a given range of changes of temperature and air flow velocity in the evaporator tank of the modular plant, the rate of evaporation is much greater than the possibility of moving the moisture mass flow of steam-air mixtures, determined from the energy balance taking into account the maximum power of insolation of 1 kW per unit of surface evaporation. To increase the insolation power per unit area, it is possible to use various solar energy concentrators using solar tracking systems in the sky.

5. Experimental studies

To determine the fresh water productivity, depending on the input power of the above-described desalination technology, two units with an evaporation surface area of 1 m$^2$ were created. The layout and appearance of the floating unit are shown in Figures 4 and 5.
Figure 4. Scheme and external experimental setup according to the first embodiment
1 - tank for heating and evaporation of sea water; 2 - thermally insulated housing of the tank of the evaporator; 3 - thermally insulated surface; 4 - fan; 5 - simulators of solar radiation (incandescent lamps); 6 - a layer of water in the tank; 7 - heat exchange sections of the condenser; 8 - tubes located with a slope to collect condensate; 9 - collector; 10 - storage tank for condensate; 11 - tap for condensate collection.

The experimental setup was created with financial support from the Skolkovo Foundation. The studies were carried out in real conditions of the water area and in the laboratory of the department of water supply and sewerage of Industrial University of Tyumen.

The main structural elements of the experimental setup: the evaporator (1) and the condenser (7) are made of stainless steel sheet. The side walls and bottom of the evaporator are coated with black porous technical rubber in order to reduce heat loss in the tank and maximize the absorption of solar energy in the evaporator during tests in real water conditions.

A fan (4) for forced circulation of the vapor-air mixture, installed in the collector (9), works on the flow of air dried and cooled in the condenser (7). Thus, the temperature and humidity of the air passing through the fan are within the permissible operating range for this equipment.

Simulation of solar insolation was achieved by installing heat emitters, which are used as electric incandescent lamps. The power input varied in the range $N = 0.7 \ldots 2.8$ kW.

The ambient water temperature from the outer surface of the condenser was 296K or 23°C. The temperature of the vapor-air mixture in the evaporation tank and the temperature of the cooled vapor-air mixture after the condenser varied depending on the input power and were measured with thermometers. The amount of condensate was determined by the volumetric method using measuring cylinders, after each hour in the course of the experiment. During research, the volume of water in the evaporator tank was kept constant.
Figure 5. Scheme and external experimental setup according to the second option
1 - tank for heating and evaporation of sea water; 2 - thermally insulated housing of the tank of the evaporator; 3 – translucent thermally insulated surface; 4 - fan; 5 - saturated air supply; 6 - connecting tubes; 7 - storage tank for condensate; 8 - connection for the 3rd and 4th channels; 9 - collector for draining dried air; 10 - substrates for scaling; 11 - collecting air pipe.

The second version of the technical solution for desalination or obtaining clean, fresh water from contaminated sources is an aggregate with a condenser buried in the ground. This version of the unit is intended for use on land, which gives it some advantages with the above floating version of the installation for clean, fresh water. The advantages are the absence of the influence of sea storms on the operation of the units.

The second version of the desalination plant with associated salt recovery includes the forced saturation of atmospheric air with water vapor in evaporators, the supply of steam-air mixture to condensers and the selection of moisture. The variant is characterized in that cold sea water is supplied to the evaporators by metering pumps of low power from tanks with a sea water temperature lower than in evaporators. To prevent the deposition of salts in evaporators, the pump capacity is established, which ensures the concentration of salts at a temperature of hot sea water in evaporators below the concentration of saturated solution. Dosing pumps create a weak circulation of sea water between the evaporators and the tank with cold sea water. At the bottom of containers with cold sea water, substrates are placed with a seed from salt, which facilitates the deposition of salts on substrates. As salt builds up on the substrates, they are removed along with the salt, freed from the salt and set back to the bottom of the tanks with cold sea water. To increase the power of solar radiation and increase the productivity of the method for fresh water, reflectors are installed on evaporators that monitor the position of the sun in the sky.
Figure 6. Scheme of desalination of sea water with associated salt recovery
1 - evaporator with a transparent surface; 2 - low-power metering pump; 3 - capacity with sea water, buried in the ground; 4 - supercharger of the vapor-air mixture; 5 - moisture condenser buried in the ground; 6 - substrates for precipitation and salt collection; 7 - pump for fresh water; 8 - reflective panels with the ability to change the angle of inclination to the horizon; 9 - drive tracking the position of the sun system, allowing you to change the angle of inclination of the reflective panels to the horizon.

To ensure low circulation of seawater between evaporators and a tank of cold water buried in the ground, low-power, metering pumps driven by solar photovoltaic batteries are used. The vapor-air mixture formed in evaporators is forcibly discharged into condensers buried in the soil with a temperature lower than the temperature of the incoming steam-air mixture, thereby ensuring moisture deposition in the condensers. The steam-air mixture blowers are driven by solar photovoltaic batteries.

To increase the power of solar radiation and the performance of the method for fresh water and sea salt on the evaporators, reflective panels are installed that monitor the position of the sun in the sky. The sun-tracking reflective panels are driven by solar photovoltaic batteries.

The method of desalination of sea water (see Figure 6) is implemented as follows. In the evaporation tank (1) with a surface that transmits solar radiation, a metering pump (2) from the tank (3), buried in the ground, serves sea water. For the supply of sea water use low-power metering pumps driven by solar energy. The steam-air mixture formed in the evaporator tank (1) is forcibly pumped into the condenser (5) by a supercharger (4), buried in the soil with a temperature below the temperature of the incoming steam-air mixture, providing moisture precipitation in the condenser (5).

Weak circulation of sea water in the evaporator (1) to prevent scaling is carried out using a low-power metering pump (2) driven by solar energy. The drive of the supercharger of the steam-air mixture (4) is also carried out due to the energy of the sun. At the bottom of the seawater tank (3), substrates (6) are placed with a seed of sea salt, which contributes to the deposition of salts on the substrates. The selection of fresh water from the capacitors (5) is carried out by a pump (7). As salts are deposited on substrates (6), they are removed from the container (3), freed from salts, and again placed on the bottom of the container (3). To increase the power of solar radiation and increase the productivity of the method for fresh water and sea salt on evaporators (1), reflective panels with a variable angle to the horizon are installed, monitoring the position of the sun in the sky, with a follow-up system (9) driven by solar energy.

6. Results
Based on the results of the experiments, graphical dependences of the mass flow rate of the condensate were constructed depending on the input power at a fixed value of the volumetric flow rate of the
circuiting vapor-air mixture and the ambient temperature (Figure 7). The upper temperature limit $T_1$ inside the heat-insulated capacity of the floating buoy was assumed to be 60°C. This suggests that the loss of hardness salts inside the evaporation tank of the desalination plant and scale did not practically form. The amount of scale formed at a water temperature of about 80°C is seven times exceeds the amount of scale at a heating temperature of up to 60°C. The operating mode of the modular plant at temperatures above 70°C is inadmissible. Figure 7 also shows the theoretical graphical dependence of the mass flow rate of the condensate on the input power, that is, without the cost of heat for heating the circuiting steam-air mixture in the installation and partial heating of the sea water that is sucked into the evaporation tank. In other words, the input power is spent only on the evaporation of sea water.

![Graph](image)

**Figure 7.** Comparison of the experimental results with the theoretical condensate productivity ($M_r$, kg/h) depending on the input power ($E_s$, kW)

The obtained fresh water productivity by modular plants is sufficient, for example, for drip irrigation of plants planted in the coastal desert zone or for greenhouses using hydroponics to grow plants [10, 11], for autonomous water supply of settlements remote from surface and underground water bodies.

### 7. Conclusions

An analysis of the experimental data showed that with an increase in the input power for heating water in the evaporator, the performance of modular desalination plants for pure fresh water grows almost linearly. Comparison of experimental data with the theoretical dependence of the mass flow rate of the condensate on the input power (Figure 7) shows that the overhead costs of the supplied heat for circulating the steam-air mixture in the installation and the heating of the incoming water to the evaporator do not exceed 30% in the input power range up to 3 kW.

The achieved volume of condensate per unit time is provided due to forced evaporation of water and circulation of the steam-air mixture by a fan. The power consumption of the fan, necessary for the circulation of the vapor-air mixture, driven by photovoltaic solar panels does not exceed 30 W.

The condenser surface area selected in the experimental setup, in this range of variation of the input power, is sufficient to condense moisture and obtain acceptable results on the performance of the desalination plant in clean, fresh water. In real conditions, the power supplied to the evaporator is more 1 kW/m² can be achieved by using solar energy concentrators and sun-tracking systems.

The water productivity of a unit with a condenser buried in the ground is lower than that of a floating unit with a condenser below the water level. This is due to the lower coefficient of heat transfer of condensation heat to the ground compared with the transfer of heat to water. To achieve
comparable performance results for both versions of the units, it is necessary to increase the heat transfer area of the condenser buried in the ground.

References
[1] Möller D. (2008) On the history of the scientific exploration of fog, dew, rain and other atmospheric water. *Special Issue: Fog Research. DIE ERDE* 139: 11–44.
[2] Brutsaert, W. (1982) Evaporation into the Atmosphere: Theory, History, and Applications. Springer, Dordrecht, 299.
[3] Al-Sulaiman FA, Zubair MI, Atif M, Gandhidasan P, Al-Dini SA and Antar MA (2015) Humidification dehumidification desalination system using parabolic trough solar air collector *Appl Therm Eng* 75: 809-816
[4] Youssefa PG, AL-Dadaha RK and Mahmouda SM (2014) Comparative Analysis of Desalination Technologies *Energy Procedia* 61: 2504-7
[5] Rajasekar K, Pugazhenthi R, Selvaraju A, Manikandan T and Saravana R (2017) Effect on air quality and flow rate of fresh water production in humidification and dehumidification system *IOP Conf. Ser.: Mater. Sci. Eng.* 183: 012032
[6] Mironov V, Ivanyushin Y, Zhernakov E and Mironov D (2018) Thermal balance in the process of fresh water production from atmospheric air using the sea waves renewable energy *MATEC Web Conf* 170: 04018
[7] Mironov V, Ivanyushin Y, Zhernakov E, Mironov D, Stepanov O and Sidorenko O (2019) Technology of receiving fresh water from forcedly saturated air through the use of solar energy *E3S Web Conf* 91: 04008
[8] Shelquist R (2009) An Introduction to Air Density and Density Altitude Calculations Available from: https://wahiduddin.net/calc/density_altitude.htm
[9] Guide to meteorological instruments and methods of observation (2008) WMO-No. 8 Available from: https://library.wmo.int/pmb_ged/wmo_8_en-2012.pdf
[10] AlShrouf A (2017) Hydroponics, aeroponic and aquaponic as compared with conventional farming *ASRJETS* 27 (1): 247-255
[11] Schröder FG, Lieth JH (2002) Irrigation control in hydroponics In: Savvas D, Passam H (eds) *Hydroponic Production of Vegetables and Ornamentals.* Embryo, Athens: 263-297