Hygroscopic method application and realization for demineralization of sea and salted water

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Abstract. The desalination of sea and salty water is one of the alternatives in solving the problem of freshwater resources shortage. Reverse osmosis and distillation desalination methods are widely used for industrial, household and potable water supply. Each method requires definite energy and material costs. That's why the problem of developing and researching the most effective energy and financial desalination plants is up to date. The aim of our research is the analysis of self-sufficient hygroscopic desalination plant operation efficiency. The comparative analysis of the most popular desalination methods has been carried out. The authors describe the desalination plant components and its operation principle. The main factors that influence plant intensity are determined. The plant developed efficiency is to increase the performance due to additional steam generation on the basis of steam-gas-liquid balanced condition law. Energy effectiveness increase is reached thanks to heat energy recycling in a condenser-separator and in a fresh water coil. The authors state that one of the best ways to accelerate the hygroscopic desalination process is to increase the initial temperature of water in barbotage area. The plant developed is characterized with high energy effectiveness, low costs and high quality of fresh water obtained.

1. Introduction

Fresh water is one of the most consumed natural resources. Every year people use 4000 km\(^3\) of fresh water from different sources, that is above consumption of other natural resources in a whole [1-3]. Global renewable water resources according to different estimations are from 42000 [4] to 43800 km\(^3\) [5] in year and distributed unevenly on land. The problem of freshwater shortage is presented because of population growth, climatic conditions and uneven population of the planet.

The freshwater shortage is evident in more than 40 countries, that are located in the arid regions of the globe and occupy 60% of the entire land surface.

Sometimes desalination of sea and salted water allows to meet the needs of the population for fresh water resources[6]. In recent decades, there has been an increase in the global market for the equipment designed for obtaining fresh water. According to the International desalination association, there are currently about 17,000 desalination plants operating in 120 countries. This method of obtain of fresh water has become the most widespread in the countries of the Arabian Peninsula, primarily Saudi Arabia, UAE, Kuwait, as well as in Spain, the United States.

Today the need of small-sized high-efficiency desalination plants is increased. Such installations are necessary both for remote regions of the planet, deprived of clean fresh water bodies and rivers, with low population density and underdeveloped infrastructure, and for shipping.

The improvement of desalination equipment in order to increase its energy efficiency and reduce costs for the production of fresh water and corresponds to the world trends in the rational use of energy resources, reducing energy consumption, as well as the use of alternative energy sources.
Therefore, the problem of developing a new energy-efficient and economical effectiveness desalination plant is relevant.

2. **Comparative characteristics of desalination methods**

The process of obtaining fresh water may be realized in two ways. The first one is reached by extracting water molecules from a solution and the second one is by removing salt ions.

In accordance with the tendencies observed in the field of desalination, there are several ways for further development of this industry.

Firstly, it’s the improvement of the desalination process and the development of new desalination plants on this basis.

Secondly, it’s the development of desalination technology based on reverse osmosis.

Thirdly, it’s the continuation of the search for economically and thermodynamically effective desalination methods such as freezing, electrodialysis, gas hydrate and hygroscopic desalination ones [7-9].

Therefore, the main technologies used in the desalination process are distillation and reverse osmosis.

During thermal distillation the source water is heated to a temperature exceeding the boiling point at given concentration of salts presented in it and pressure followed by boiling.

The thermal desalination method is based on the water phase transformations and allows to get the final product, which is cleaned from dissimilar impurities without any chemically affect. However, this process requires significant energy costs. It takes more than 2500 kJ / kg for preheating and subsequent evaporation. Therefore, this method is used for water desalination in small quantities as well as for household needs and chemical laboratories.

Water demineralization by freezing is based on the fact that, while cooling, pure water will crystallize first. Desalination process inside plants includes the following steps: crystallization-ice formation; ice and brine separation; ice melting. This process requires significant capital costs, significant energy costs, including the ice separation process. In addition, the disadvantages of desalination by freezing are the complex design of the plants, the strong dependence of the operating parameters on season and weather conditions; the difficulty of predicting the degree of purification; the need to observe the freezing-melting cyclessequence.

Desalination methods in which no phase transition occurs include the reverse osmosis, chemical, ionic methods and electrodialysis. The physical essence of reverse osmosis desalination is the diffusion of substances through a semi-permeable membrane that separates the solution and the pure solvent. This method is not practically applied in countries with high ambient temperatures (over 32 °C). It happens because in this case the process of hydrolysis of the membranes is more intensive and shortens the operation period. Therefore, the reverse osmosis desalination method requires significant economic costs for its implementation.

In the process of electrodialysis electrochemical separation of salts from electrolyte solutions occurs due to their transfer through ion-selective membranes under the influence of an electrical field. This desalination method requires preliminary preparation of source water. In addition, it is not used for salt water desalination due to the fact that with an increase in the potential difference between the electrons, the energy consumption increases significantly and the process of membrane tear is more intensive. The ionic desalination method is based on the absorption of salts dissolved in water by passing the initial product through sorption filters made of ion-exchange resin. Chemical desalination lies in introducing precipitating reagents into desalinated water which when interacting with salt ions form a precipitate. Because of the complexity of execution and high consumption of reagents used in the process of demineralization chemical and ionic desalination methods are not widely used.

One of the promising desalination methods due to its energy efficiency is the hygroscopic desalination method [10]. When implementing this method, sea water is evaporated using an air stream, and then water vapor is condensed, that is a natural psychrometric temperature difference is used as an energy source. Accordingly, it is quite similar to the mechanism of fresh water natural formation.
The main factors determining the choice of desalination method are quality parameters of the resulting product; operating principle and installation cost; the costs of its maintenance and installation; properties of the treated water; installation performance and its location.

The analysis of the efficiency of the aggregate-technological schemes for various desalination methods operating on the initial product of the same quality shows that the energy consumption for them is different. In its turn, the value of energy costs is determined by the process parameters, the design of the desalination plant, the layout of the technological scheme, the presence or absence of waste energy regeneration.

The energy efficiency of the desalination process largely depends on the energy losses that occur while creating the “driving forces” of this process: temperature differences, pressure differences, etc. Therefore, the improvement and the development of new desalination plants is associated with the issue of reducing energy losses in particular with heat recovery.

3. Design of the hygroscopic description plant and features

Hygroscopic plants are called desalination plants, which include contact apparatus in which heat and mass transfer between the liquid and gas occur [11].

The development of an autonomous hygroscopic desalination plant is aimed at reducing the cost of producing fresh water, increasing the energy efficiency of the desalination process, creating environmentally friendly plants that can compete in the desalination technology market.

The original desalination plant, developed by the authors, contains the capacity of desalinated water, an evaporation chamber, and a collection tank of fresh water. Desalination plant is made according to a closed air flow pattern with built-in coils of a water heater and a distillate cooler. The operation of such installations is based on the law of equilibrium of vapor-gas-liquid mixtures.

The main structural elements of hygroscopic desalination plants are heat exchangers, mechanisms, devices, tanks, pipelines, and control and measuring materials.

The desalination plant schematic diagram is shown in Figure 1 [12]. It includes an aluminum cylindrical evaporation chamber, in the upper part of which a coil connected to the solar collector is installed below the level of desalinated water; a bubbler device located under the heating element and made in the form of a flat spiral with holes; a discharge device for moving air masses and powered by a solar battery; a condenser-separator in which the process of drying air is carried out; a coil used to heat desalinated and cool fresh water.

![Diagram of the self-sufficient desalination plant](image)

1 – desalinated water tank; 2 – evaporation chamber; 3 – capacity-collection of fresh water; 4 – overflow pipe; 5 – valve; 6 – water level sensor; 7 – removable bottom; 8 – removable cover; 9 – zone vapor mixture; 10 – heating element; 11 – solar collector; 12 – bubbling device; 13 – condenser-separator; 14 – coil; 15 – pipe; 16 – air blower; 17 – solar battery; 18 – vapor-air mixture tube; 19 – heating zone; 20 – brine drain valve

**Figure 1.** Schematic diagram of the self-sufficient desalination plant
The capacity of desalinated water is installed above the evaporation chamber. Accordingly, demineralized water enters the installation body by gravity. Water with a high salinity (brine) from the heating zone above the bubbler due to the higher density falls to the bottom of the evaporation chamber. Brine removal is carried out through the brine drain valve.

The desalination plant is equipped with all necessary fittings, automatic equipment for regulating and monitoring the installation mode.

When designing desalination plants, it is necessary to consider the characteristics of the working media circulating in the body of the unit. For example, sea or brackish water is characterized with its corrosion. That’s why it is necessary to install elements that have direct contact with this medium from the material resistant to such effects. Therefore, heat exchangers and a bubbler device included in the installation are made of copper.

In addition, the use of sea water as a working fluid requires knowledge of its thermodynamic characteristics. It is important for conducting a thermo-economic assessment of the processes occurring in desalination plants. In this regard, it is necessary to take into account that at the beginning of the desalination process, sea water can be considered as a diluted solution, that is, as ideal, and subsequently with an increase in concentration, it is necessary to take into account changes in the properties of sea water due to the presence of salts in it.

Air masses the process of saturation can be carried out under atmospheric pressure, as well as under vacuum.

The operation of the installation under atmospheric pressure implies that in this case: there is no need to provide a permanent vacuum, requiring tightness and constant energy consumption; the steam-air mixture has a higher density, respectively, takes up a smaller volume, which reduces the size of the installation channels; there are no special technical means for input and output of fluid flows from the cavity under vacuum. However, under such conditions the rate of salt deposition on heat exchange surfaces is higher. Based on the analysis of the advantages and disadvantages of both options, a desalination system that operates at atmospheric pressure is adopted.

During the installation operation energy is spent on the process of heating desalinated water, as well as on the movement of air masses along the circuit.

The process of heating the intermediate coolant circulating in the circuit of the heating element is carried out in the solar collector. The transfer of an intermediate coolant whose boiling point is higher than the normal boiling temperature of desalinated water is carried out naturally. The use of solar energy to generate thermal and electrical energy allows us to achieve the autonomy of the installation.

4. Heat and mass exchange processes in desalination elements

The energy efficiency of desiccants of a hygroscopic type consists in increasing the performance of the installation due to the additional generation of steam thanks to the difference in the temperature of the thermodynamic equilibrium of the liquid and the temperature of its saturation at the same pressure.

The operation of the installation under study includes: the heating process and the air flow through the bubbler device; the process of air movement saturation, accompanied by moisture exchange between desalinated water and air masses; its subsequent drying in the condenser-separator; heating of desalinated water as a result of its contact with the surface of a fresh water coil, a condenser-separator and a heating element; the process of heating fluid in a solar collector.

As a result of the heated air stream contact with a layer of hot water, its moisture content increases, temperature, enthalpy, and humidity change. The supply of heat in the bubble zone intensifies the process of air saturation with moisture. The air bubbling into the layer of heated water intensifies the processes of heat and mass transfer between gas and liquid media. This phenomenon is due to the development of the interaction surface, which arose due to the high dispersion of the bubbles supplied to the liquid [13].

During the installation operation the processes of coupled heat and mass transfer occur, the intensity of which is determined by the initial conditions of the processes, the design features of the installation.
The dependences analysis describing the processes of mass transfer occurring in contact devices shows that various quantities can be used as potentials characterizing the driving force of mass transfer: molar or mass concentrations of components, their partial pressures, and gas moisture content. When calculating these processes, it is convenient in this case to use the difference in the gas moisture content. The “driving force” of the heat transfer process is the temperature difference. Since the partial pressure of steam in the air is an unambiguous function of moisture content, the amount of evaporating water as a result of contact with air can be determined by the equation:

\[ dW = \beta_d \cdot dF \cdot \frac{d_e - d}{1000}, \]

where \( \beta_d \) is the moisture transfer coefficient, referred to the difference in moisture content, kg / (m² · s (g / kg)); \( d_n \) is the air moisture content in the boundary layer of a liquid at its surface temperature, g / kg; \( d_a \) is the air moisture content in the environment; \( dF \) is the elementary platform for moisture exchange, m².

Two temperature differences are distinctly formed at the boundaries of the boundary layers: the difference between the air temperatures of the wet thermometer and the dry one and the difference between the air temperature of the wet thermometer and the temperature of the liquid. The first temperature difference does not determine the heat and mass transfer process, since the gas temperature entering it does not determine the air temperature using a dry thermometer. The second difference determines the heat and mass transfer, since the temperatures included in it uniquely determine the enthalpy of such medium as air and liquid.

The process of the air flow saturation with moisture is accompanied by the corresponding elementary processes: diffusion processes, heat and mass molar transfer, non-isothermal mass conductivity, which mutually influence each other. When considering the jointly occurring processes of heat and mass transfer, it is necessary to take into account their mutual influence on each other, which is caused by the occurrence of stefan flow [14], thermal diffusion, and diffusion heat conduction. In this case, the basis of modern methods for calculating these processes are the differential equations of motion, continuity, and diffusion.

The determining factors in the intensification of heat and mass transfer processes in the installation are the high relative air velocity, developed contact surface; high dispersion of air masses; uniform distribution of speeds, dispersion and air mass in the volume of the reaction; space sufficient contact time [15].

5. Research of a desalination installation operation
In order to verify operability, determine optimal operating conditions and confirm theoretical research, a series of experiments was conducted on the desalination plant created for this purpose.

The studied hygroscopic installation is designed to produce drinking-quality water. In this regard, the total mineralization in the condensate at the outlet of the desalination plant was taken at the level of 1 g / l. In this case, total mineralization is understood as the total concentration of anions, cations, and undissociated organic substances dissolved in water, expressed in grams per liter. The total salinity of the water coincides with the dry residue.

The dry residue in the condensate is determined by evaporating a certain volume of water, pre-filtered through a paper filter, followed by drying the residue to constant weight at a temperature of 105-120 ° C. Water heating in the installation is ensured by a solar collector with an absorption plate area of 4.4 m², and a supercharger with a 60 W panel of solar cells.

The main factors affecting the efficiency of the installation are the temperature of the water and the air in the bubble zone.

During the experiment, the water temperature was maintained at a level of 70-100 ° C, and the air temperature varied within 20-100 ° C, the pressure and air flow remained constant. Air masses enter a bubbler with a humidity of 40%.
The initial water temperature in the bubbling zone has a significant effect on the plant’s productivity; with its increase, the productivity increases parabolic. The ability of air to retain moisture increases with increasing temperature of the water with which it comes into contact.

The dependence of the plant capacity on the water temperature in the bubble zone is shown in Figure 2.

![Figure 2. Dependence of plant performance on the initial water temperature in the bubble zone](image)

The productivity of the installation decreases with increasing temperature of the air bubbled into the layer of heated liquid. This relationship is shown in Figure 3. Changes in air temperature slightly affect performance.

![Figure 3. Dependence of plant performance on the initial air temperature in the bubble zone](image)

Summarizing all of the above, we can conclude that the water temperature in the bubble zone has a significant impact on the performance of desalination plants of a hygroscopic type, and its increase is one of the ways to intensify the process of producing fresh water.

### 6. Conclusion

The efficiency of the developed desalination plant of hygroscopic type of sea water consists in a significant increase in productivity due to the additional generation of steam, based on the law of equilibrium of vapor-gas-liquid mixtures, the complete utilization of the heat of condensation of the vapor-air mixture in the condenser-separator, and the cooling of the condensate in the fresh water coil. These circumstances reduce the cost of thermal energy for water heating processes in the installation. As the source of thermal and electric energy is solar energy the installation can be used especially in regions devoid of clean fresh water bodies and centralized sources of electric and thermal energy.
So, the advantages of a hygroscopic desalination plant include the simplicity of its design and operation, low scale formation that does not prevent evaporation in the contact apparatus, the possibility of more complete use of low-potential heat, the possibility of using any apparatuses, including intensified contact ones, low energy consumption, the possibility of maximum evaporation of the brine to bring to a dry residue.

The disadvantages of plants of this type include: increased corrosiveness of water in contact with air, reduced productivity with decreasing temperature of the heating medium. To reduce the dimensions of the hygroscopic type installations it is necessary to decrease the pressure of the media in the evaporator and increase it in the condenser.

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