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Energy Efficient and Environmentally Friendly Console Desalination Plant with Low Temperature Distillation

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Abstract

This article describes the console plant for desalination of saline water, which uses a quasi-adiabatic process with difference of the water temperature lower than 5 °C. That provides ecological safety when the seawater is used as a source of saline water. The main element of the installation is a patented heat mass transfer device with a huge surface area of contact. Only a small portion of saline water flows through device, which can be pre bactericidal treated, such as of quartz. In this case, the cold of the desalination plant can be utilized that allows using this cooled and dehumidified air for air conditioning. The article presents a thermodynamic diagram processing air and block diagram of this desalination plant, and an analysis of similar devices for desalination.

Keywords: desalinator, sea water, air conditioning, low temperature distillation

1. Introduction

A problem of freshwater making is becoming one of the global issues of the humanity in the new millennium (Heimbuch, 2010). Freshwater shortage is already sharply felt on the territory of over 40 countries located in arid regions of the world and amounting to over 80% of total land surface.

Shortage of fresh water is progressing in industrially developed countries, such as the USA and Japan, where freshwater demand for daily living needs, agriculture and industry exceeds the available freshwater resources. In countries like Israel and Kuwait where the precipitation level is very low, fresh water resources do not correspond with the demand, moreover, this demand is undoubtedly increasing due to national economy modernization and population growth.

The global freshwater consumption in the beginning of the 21-st century has reached 120-150 bcm per annum. The growing world freshwater shortage can be compensated by desalination of salty(salt content over 10 g/l) and saltish (salt content 2-10 g/l) ocean, sea and groundwater, which amount to 98% of all water across the globe.

Salinity is an important parameter of sea water in the process of desalination. It is understood as mass (in grams) of dry salts (predominantly NaCl) in 1 kg of sea water. Average salinity of the world ocean water is constant and amounts to 35 g/kg of sea water (Lipa, 2010; Khorn, 1972).

High concentration of salts makes sea water unfit for potable and domestic purposes. That is why it is necessary to desalinate it, i.e. perform its treatment in order to decrease the concentration of dissolved salts down to 1 g/l. Desalination of water may be performed by chemical (chemical deposition, ionic exchange), physical (distillation, reverse osmosis or hyperfiltration, electrodialysis, freezeout) and biological methods using the capability of some photosynthesizing algae to selectively absorb NaCl from sea water (Kimm and Logan, 2011).

Over the past few years new alternative methods of sea water desalination have been proposed with the use of supersonic, acoustic, ballistic waves, electromagnetic fields, etc.

The diversity of the existing methods (Slesarenko, 1999) of freshwater making is explained by the fact that none of them can be considered universal and acceptable for different specific environments (Mosin, 2011; Mosin, 2012).

Notably, specialists' efforts are mainly concentrated on developing high capacity centralized desalination units ("Zerkalo nedeli. Ukraina", 2014) and virtually no attention is paid to local, individual desalination units.

Meanwhile there is a large number of consumers which need only from 1 to 5-6 m³ of fresh water daily (Lianying, 2013). These include small cafes, restaurants, offices, public service establishments, workshops, residential houses, cottages, greenhouses, small farms and a number of other facilities.

The experience gained in the last few years by heat power industry conclusively demonstrates that heat supply problems can be resolved in the most efficient way only on condition of competent and professional combining centralized heat supply from thermal power plants or district boiler houses and individual boiler houses. There is no doubt that this is the most promising way for optimal solution of freshwater supply problems.

2. Methods

A brief description of most commonly used modern desalination methods is given below.

2.1 Chemical Desalination

Chemical method of desalination provides for injection of special precipitating agents into sea water. These agents interreact with ions of salts dissolved in sea water (chlorides, sulphates) and form insoluble precipitates. Due to the fact that sea water contains a lot of dissolved substances, reagents consumption is rather significant and amounts to about 3-5% of the desalinated water volume. Substances which are able to form insoluble substances with sodium ions (Na^+)and chloride ions (Cl^-) include silver salts (Ag^+) and barium salts (Ba^{2+}), which during salty water treatment form precipitating argentic chloride (AgCl) andbarium sulphate ($BaSO_4$). These chemicals are expensive and the reaction of precipitation with barium salts takes a lot of time, barium salts are toxic. That is why chemical precipitation is very rarely used for water desalination.

2.2 Distillation

Water distillationis based on difference in the composition of water and steam, generating from it. The process is conducted in special distillation units – desalinators by means of partial evaporation of water and subsequent steam condensation. In the process of distillation a more volatile component (low-boiling) transforms into vapour phase in a larger quantity than a less volatile (high-boiling). That is why during condensation of generated vapours low-boiling components transform into distillate, and high-boiling components transform into stillage residue. If not one but several fractions are distilled from the initial mixture such distillation is called fractional (reduced). Depending on the process conditions regular and molecular distillations are differentiated (Siyrde, 1991).

Distillation desalination unit consists of evaporator *1*, supplied with a heat-exchanging unit for transfer of required amount of heat to water; heating element *2*for partial condensation of steam, coming out of the evaporator (at fractional distillation); condensing unit *3*for condensation of bleed steam; pumpunit*4*; distillate tank*5*and stillage residue*6* (Figure 1).

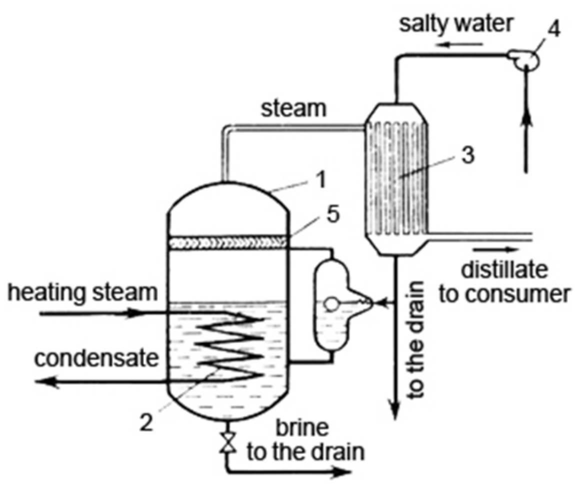

Figure 1. Single-stage distillation desalinator flow diagram

1 – evaporation chamber housing; 2 – heating element; 3 – condensing unit; 4 – pump unit; 5 – distillate tank.

Modern distillation desalinators are divided into single-stage, multi-stage with tubular heating elements or evaporators, multi-stage flush ones and vapour compression ones (Gelperin, 1981).

Multistage evaporator (Figure 2) consists of a range of sequentially operating evaporating chambers with tubular heating elements. The heated salty water moves inside the heating element tubes, heating steam is condensing on the outside surface. At the same time the heating and evaporation of water in the first stage is performed by steam of working boiler operating on distillate; secondary steam of the previous evaporating chamber is the heating steam of next stages. This unit is capable of generating about 0.9 tons of fresh water per 1 ton of primary steam. Heat consumption for generation of 1 kg of freshwater in a single-stage distillation desalinator amounts to about 2400 kJ.

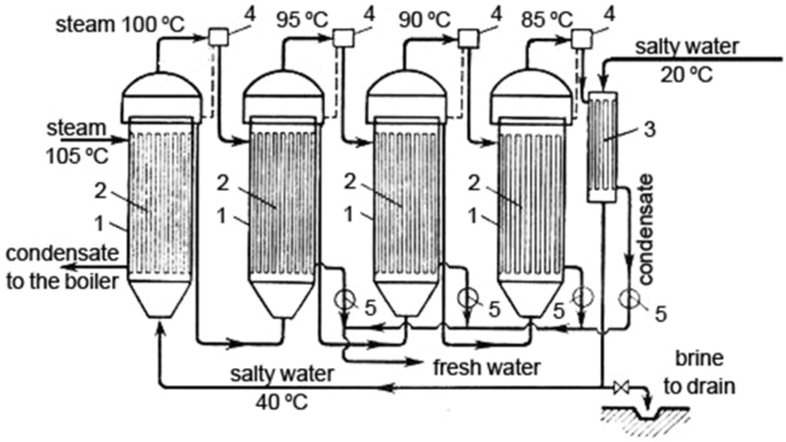

Figure 2. Flow diagram of single-stage distillation desalinator with tubular heating elements
1 – evaporation chambers of 1, 2, 3 and 4 stages; 2 – tubular heating elements; 3 – trim condenser; 4 – drop catcher; 5 – pump unit.

The main advantage of multi-stage distillation desalination units is the fact that per unit of primary steam one can obtain a lot more desalinated water. For example, single-stage evaporation generates about 0.9 desalinated water per 1 ton of primary steam, whereas units with 50-60 stages generate 15-20 tons of desalinated water. Specific power consumption in distillation units amounts to 3.5-4.5 kW hr/m^3 of distillate.

Implementation costs of any of the distillation process option is associated with high consumption of thermal power, amounting to 40% of the cost of the produced water. Nuclear and thermal power plants are used as sources of thermal energy. Combination of distillation unit with thermal power plant using mineral or nuclear fuel, so called a multipurpose power installation, makes it possible to provide all kinds of power services to the industrial region with most rational use of fuel. Solar distillers are used in areas of deserts in the South and in waterless islands. They produce about 4 liters of water daily from 1 m^2 of surface subjected to solar radiation.

The efficiency of distillation evaporators is limited by scale formation in the hot brine circulation system. In the course of sea water evaporation from distillation evaporator salt solution becomes more concentrated, and eventually it settles on the walls of the unit in the form of a scale out of hardness salts, consisting mainly from calcium chlorides and calcium carbonates($CaCO_3$,$CaCl_2$) and magnesium ($MgCO_3$, $MgCl_2$), which deteriorates the heat exchanger walls thermal conductivity, leads to destruction of tubes and heat-exchange equipment. This requires the use of special anti-scaling additives, which significantly increases the power costs for distillation up to 10 kW hr/m^3 of desalinated water. That is why in the past few years other methods of sea water desalination were proposed, the ones that are not associated with necessity of water evaporation and condensation.

2.3 Ionic Exchange

The method is based on the property of hard polymeric resins of different degree of cross-linking, covalently connected with ionogen groups (ionites), to reversibly exchange with ions of salts dissolved in water (counter-iones).

Depending on the charge ionites are divided into positively charged cation exchangers (H^+) and negatively charged anion exchangers (OH^-). In cation exchangers – substances, similar to acids, anions are represented non-water-soluble polymeric compounds, and cation exchangers (Na^+) are non-stationary and exchange with cations of solutions. As opposed to cation exchangers anion exchangers are alkali in terms of chemical structure, the insoluble structure of which is formed by cations. Their anions (usuallyOH^- hydroxyl group) are capable of exchanging with anions of solutions.

The process of ionic exchange water desalination involves sequenced passing of water through fixed bed of ionite in periodic process or reverse-flow of water and ionite in continuous process (Figure 3). This process involves cations and anions of the salts of the conditioned water interlinking with ionites which results in water desalination. Ratio of ion-exchanger, anion exchanger and cation exchanger is usually from 1:1 to 1.5:1.0 in terms of mass.

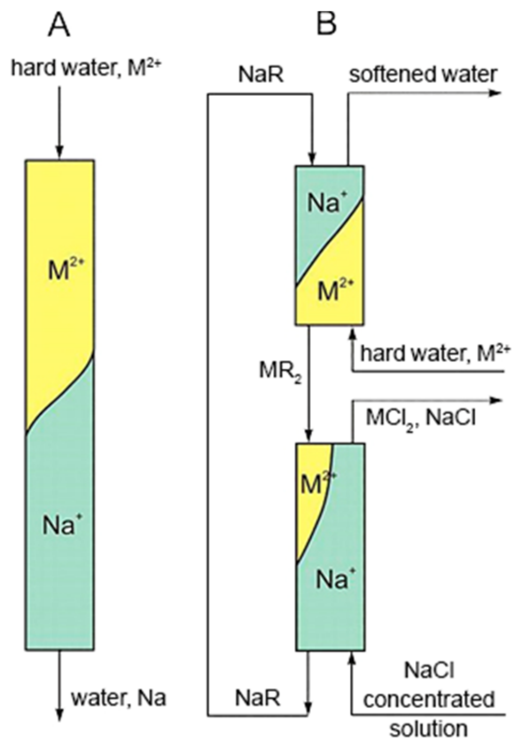

Figure 3. Ion-exchange water desalination process flows ($M^{2+} = Ca^{2+}$, Mg^{2+}) on a fixed bed of ionite (a) and in reverse-flow (b) with moving layers of ionite (NaR, MR_2) and water flows

Ion exchange kinetics involves3succeeding stages: moving of the sorbed ion to the ion-exchanger globule surface (1), ion exchange (2), moving of the displaceable ion inside the ion-exchanger globule and away from its surface in the solution(3).

The speed of ion exchange is influenced by the following factors: availability of the fixed ions inside the ion-exchanger framing, ion-exchanger granular size, temperature, solution concentration. Total speed of the ion exchange process is determined by totality of the processes in solution (diffusion of counter-ions to granule and from ion-exchanger granule) and in ion-exchanger(diffusion of counter-ions from the surface to the ion-exchanger granule center and in reverse direction). In conditions close to real environment of water treatment, a limiting factor determining the speed of ion exchange, is a diffusion of ions inside the granule of ion exchanger.

Exchange capacity of ion-retardation resins is gradually decreasing, and eventually, runs out. In this case a regeneration by acid solution (cation exchanger or alkali liquor (anion exchanger) is required, which restores the initial chemical properties of resins. Cation exchanger is regenerated by 5% solution of sulphuric acid sequentially passed through cation exchanger until acid reaction is observed. Sulphur acid specific consumption amounts to 55-60 g/g·E of sorbed cation exchangers. Anion exchanger is regenerated by 5% solution of sodium carbonate orsodium hydroxide with specific consumptionof70-75 g for 1 g·E. of blocked anion exchangers.

Ion exchange is used for producing desalinated and softened water in thermal and nuclear power industry, in non-ferrous metal industry – during integrated hydrometallurgical ore treatment, in food-manufacturing industry, in medical industry for producing antibiotics and other types of medicine, as well as for waste waters treatment for setting up recirculating water supply. At the present time ion exchange methods of extracting valuable minerals from ocean water are being developed.

Industrial units for implementation of ion exchange are subdivided into 3 groups: mixer/settler units, units with moving and fixed beds of ion-exchange material. Units of the first type are most commonly used in metal industry. In units with fixed bed of ion-exchange material initial and desalinated solutions are fed in one direction (direct flow circuit) or in opposite directions (reverse-flow circuit).Such units are used for ion exchanging purification of solutions and for sea waters of tening and desalinating. In continuously operating reverse-flow units moving ion-exchange material is moved from top downward under action of gravity. In terms of design reverse-flow units are subdivided into 3 groups: with suspended or bubbling bed of ion-exchange material, with continuous moving bed of ion-exchange material and with solution moving through ion-exchange material.

Depending on the given degree of water desalination single-stage, two-stage and three-stage ion-exchange units are designed. Residual salt content at single-stage ion-exchange desalination amounts to20 mg/l. For producing water with salt content up to0.5 mg/l units with two-level system of H^+- and OH^-- ionization.

Ion exchange method of water desalination has some advantages: simplicity of equipment, small consumption of source water for own needs (15-20% of unit capacity), small consumption of electric energy, small volume of waste waters.

Disadvantage of ion exchange method – comparatively high consumption of chemicals, complicated process, which is limited by the initial level of salt content of the conditioned water, and determined by costs. Cost efficiency of ion exchange method of water desalination is usually limited by the initial content of dissolved salts 1.5-2.5 g/l. However, when necessary, when water cost efficiency does not matter much, this method can be used for desalinating water with quite high salt content.

2.4 Reverse Osmosis

Desalination of water by means of reverse osmosis involves passing the sea water through semi-permeable membranes under pressure significantly exceeding the differential of osmotic pressures of fresh and sea waters (for sea water 25-50 atm (Dytnerskiy, 1978)). Such membranes are manufactured from polyamide or acetate cellulose and are produced in the form of hollow fibers or rolls. Small water molecules can freely penetrate through the micropores of these membranes, whereas larger ions of salt and other solids are blocked by the membrane.

Reverse osmosis is used since the beginning of 70-s in different technologies of water cleaning from different types of solids, including for water desalination (Svitsov, 2006). Modern industrial reverse osmosis units include fine water filter, chemical reagents preparation system, high-pressure pump, filtering modules unit, chemical washing unit.

The pipes of reverse osmosis water desalination units are manufactured from porous material lined from the inside by cellulose acetate film, functioning as a semi-permeable membrane. Desalination unit consists of a large number of identical pipes laid in parallel to each other, through which sea water is pumped continuously by means of a high-pressure pump(50-100 bar), and two flows are channeled out– desalinated – permeate water, and water with concentrated salts – a concentrate which is dumped into the drain (Figure4). The fresh water flow thorough the membrane is proportionate to the applied external pressure. Maximum pressure is determined by own characteristics of the reverse-osmosis membrane. Under over-pressurization the membrane can break and get blocked with solids present in water or it can allow passage of too much dissolved salts. When the pressure gets too low the process gets slower.

Reverse osmosis has significant advantages compared to other methods of water desalination: power consumption is comparatively low, units design is simple and compact, their operation can be easily automated. Reserve osmosis system control is conducted in semi-automatic and automatic modes. Sludge inhibitors are used to inhibit undesirable deposits of salts in the pipes cavities. Chemical washing system is used for removing the salts settlings from the membrane surface. Flow-through salt content meters and pH-meters are used to control water treatment quality and pH level. Permeate water and concentrate consumption control is performed by flow-through flow meters.

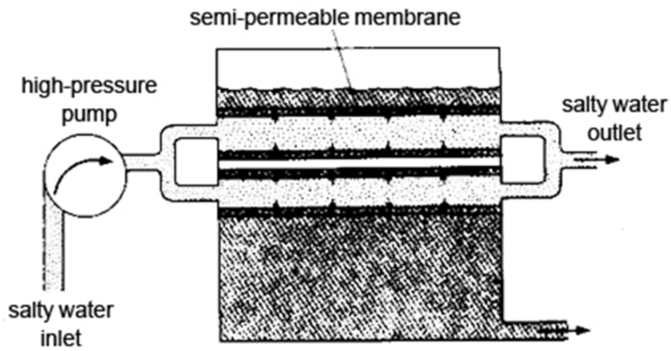

Figure 4. Reverse osmosis water desalination process diagram

Degree of water desalination and membrane capacity in terms of desalinated water depend on different factors, first and foremost, on general salt content of the source water, as well as salt content, pressure and temperature. For example, desalination of salty well water with 0.5% of dissolved salts, under 50 atm pressure during 24 hrs makes it possible to generate about 700 l of fresh water from 1 m^2 membrane (Orlov, 2007). Since a lot of very thin pipes are required for obtaining a large surface, reverse osmosis is not very common for generating large quantities of fresh water. However, this process appears quite promising, if in future some improved low-pressure highly-selective energy-efficient membranes will be developed, especially for desalination of salty water from wells. This water features lower concentration of dissolved salts compared to sea water, which makes it possible to desalinate it at lower pressures.

2.5 Electrodialysis

This process of membrane separation is based on the ability of ions of salts dissolved in water to move through the membrane affected by the electric field gradient (Kagramanov, 2007). At that cations move in the direction towards the negative electrode (cathode), and anions move in the opposite direction towards the positively charged electrode (anode). Cations and anions are divided with the use of special ion-selective membranes, permeable for ions. As a result in the volume limited by the membranes salts concentration declines.

Ion-selective membranes used for electrodialysis are manufactured from the thermoplastic polymeric material (polymethylene, polypropylene) and ion-exchange resins in the form of flexible sheets of rectangular shape. They have high mechanical strength, high electrical conductivity and high permeability for ions. In addition, they have high selective capacity and low electric resistance from 2 O/cm^2 to 10 O/cm^2 for a unit of ion-exchange membrane surface. Membrane operating life is 3-5 years on average.

Electrodialysis desalinators are multi-chambered units of press filter type, consisting from chambers, limited from one side by cationite membrane, and from the other – anionite membrane, dividing the volume of the unit into a multitude of cavities.Chambers are located between the cathode and anode, with direct current flow (Figure 5).

Desalinated water is channeled into desalination chambers, where affected by electric field cations and anions of salts dissolved in water move in opposite directions, towards cathode and anode, accordingly. Since cationite membranes in the electrical field are permeable for cations, but not permeable for anions, and anionite membranes are permeable for anions, but not permeable for cations, selective division of certain types of salts ions is performed in desalination chambers. At that salts removed from water are concentrated in brine chambers where they are removed from along with the washing salty water.

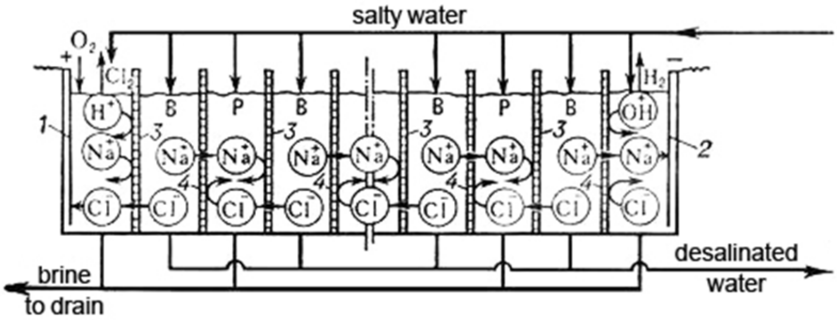

Figure 5. Multichamber electrodialysis desalinator flow diagram1 – anode; 2 – cathode; 3 – anionite membrane; 4 – cationite membrane; B – desalinated water; P – brine

Electric energy consumption for water desalination by means of electrodialysis depends on initial salt content of source water subject to desalination (2 W·hper 1 l for desalination of water with salt content 2.5-3 g/land 4-5 W·h for 1 l for desalination of water with salt content 5-6 g/l). Fresh water yield in electrodialysis units amounts to 90-95%.

Electrodialysis desalination units are used for desalination of sea water during generation of potable and process water, during desalting waste waters of electroplating industry (galvanic wastes), for concentrating waste waters, containing valuable components (for example, precious metals) before subsequent recovery of these components. Most commonly the electrodialysis process is used for desalting water containing no more than 10 g/l of dissolved salts. In this case the electrodialysis process is more economical compared to reverse osmosis and distillation. Electrodialysis process can also be used for solutions concentrating. Due to that electrodialysis is used at extraction of sodium chloride (NaCl) and other salts from sea water. Electrodialysisis also used for pretreatment of water for thermal power plants.

The advantage of electrodialysis compared to reverse osmosis is that it uses thermally and chemically more enduring membranes, which makes it possible to desalinate water under high temperatures.

2.6 Freezing

This method is based on the fact that in natural environment the ice, generated from sea water, is fresh, since ice crystals under temperature lower than the temperature of freezing are only formed from water molecules (cryoscopy phenomenon) (Orekhov and Obrezkov, 1980). During artificial slow freezing of salty sea water fresh ice is generated around the centers of crystallization. This fresh ice has a hexagonal needlelike structure with average density of 930 kg/m^3. At that the concentration of solution and its density are increased in the channels between needles, and since it is heavier, it settles down as it freezes. During subsequent separation, washing and thawing of crystal ice fresh water with salt content 500-1000 mg/l is generated.

Sea water freezing is performed in crystallizer tanks (contact, vacuum, out-of-contact heat exchange) in conditions of direct contact of the coolable solution with coolant medium - gaseous or liquid one.

In order to achieve optimal desalination of the sea ice fractional melting under temperature 20 °Cwith circulation and ice crystals separation from mother solution by means of filtering, hydraulic pressure and centrifugal action is used.

This method is used for concentrating nonedible products, for sea water desalination, concentrating and separation of chemical solutions, etc. It is rather simple and economical, but it is energy consuming and requires complicated equipment. That is why it is rarely used in practice.

3. Discussion

The analysis of the sea water desalination methods considered above shows that the choice of particular method depends on initial salt content and on requirements to quality and salt content of desalinated water, as well as to cost/performance ratio.

It is worth noting that none of the considered methods is appropriate for setting up individual desalination units, since specific additional requirements apply to them. In the first place such requirements include minimal cost of equipment and minimal consumption of heat and electric power, as well as small size, simplicity and low cost of maintenance, high reliability and environmental security.

Energy-efficient desalinator with low-temperature distillation, which is proposed by the authors, meets the above-mentioned requirements. Its basic outline is presented in Figure 6.

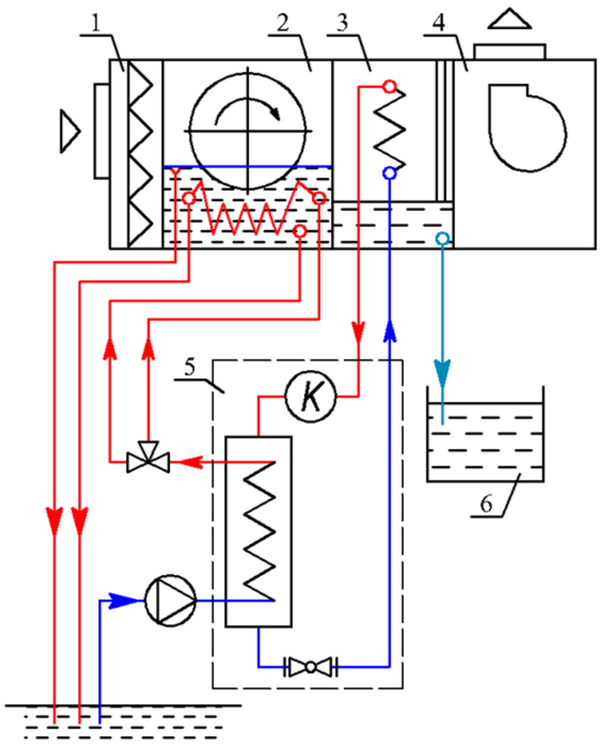

Figure 6. Basic outline of energy-efficient desalinator with low-temperature distillation

Desalinator (Tarabanov *et al.*, 2014) consists of the receiving unit for intake and filtration of the ambient air *1*, low temperature humidification unit *2*, which contains a spinning disk humidifier designed by the authors (Tarabanov *et al.*, 2014; Prokofyev, 2013), a condensation unit with a surface-type air cooler and a eliminator *3*, a ventilating unit for air moving *4*, a refrigerating unit *5* with cooling of condenser with sea water, a pump for intake and discharge of desalinated water and a piping system, and tank *6* for gathering of fresh water.

The main element of the desalinator which ensures its high energy efficiency is a spinning disk humidifier (SDH), presented in Figure 7.

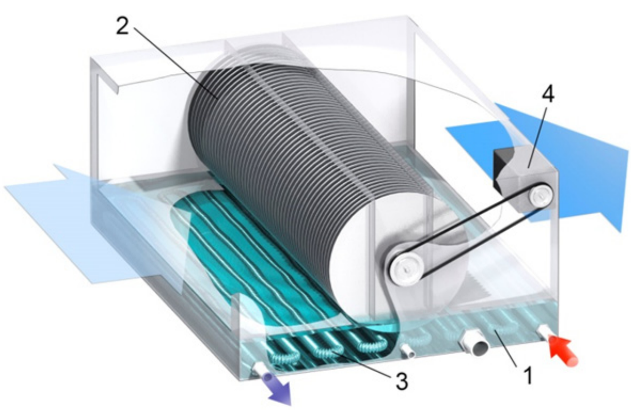

Figure 7. Overview of a spinning disk air humidifier (SDH)

SDH consists of a housing with a tray *1*. The housing contains a rotary *2*assembled on a horizontal shaft from flat smooth disks 330 mm diameter installed with a 2 mm gap from each other. The lower part of the rotary is lowered into the tray *1*with sea water where a coil *3*is located. The coil is manufactured from stainless corrugated tube with wall thickness 0.3 mm.

The rotary is spinning along the air flow with the help of a small motor-reducer *4* with frequency 6-10 rpm. Rotary spinning creates a fine water film on the surface of the disks and it interacts with the air coming through in slit channels between the disks. High efficiency of water evaporation is provided by a huge specific surface of the header, amounting to 800 m² per 1m³ of the rotary and high air velocity – up to 7 m/s in the rotary clear opening.

The important feature of SDH is its ability to operate under negative ambient air temperatures(during author's experiments down to minus 25°C) with 25 °C water coming into the tray or coil.

It is especially important from the practical point of view that only a small portion of water can be channeled into the tray, the portion which is necessary as makeup for evaporating liquid and means of maintaining a static water level in the tray. This makes it possible to perform efficient bactericidal treatment of sea water, coming into the tray, and gives the opportunity to use cooled and moisture-free air for purposes of air conditioning.

Desalinator is operated in the following way. Ambient air from the feed section after preliminary treatment goes into SDH where it is humidified with warmed sea water, fed into the tray and coil after cooling of the refrigeration condenser. Air is humidified under low temperature since sea water is warmed only by 5-6 °C in the condenser and is additionally cooled in SDH due to partial evaporation.

Humidified air, close to saturation, is fed on the surface-type air cooler, where it is cooled below the dew point temperature with cold water from the refrigeration unit evaporator. At that water steam condenses and settles down, after that it is caught by a drop separator, accumulated in the tray under the air cooler, and then by gravity it flows into the collecting tank.

The process of air treatment and obtaining of condensate is shown at h-x diagram of the moist air at Figure 8.

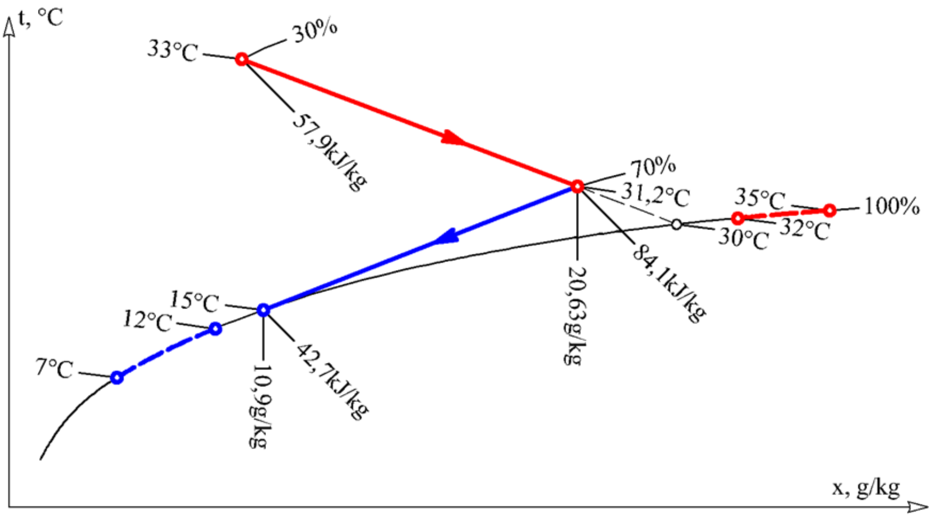

Figure 8. Process of air treatment at h-x diagram

Using refrigeration cycle (reverse Carnot cycle) makes it possible to significantly reduce power consumption for desalination, since the refrigerating factor of modern refrigeration units (coefficient of performance, COP) with a water cooled condenser reaches 6-6.5 kW of cold/kW of electric power.

Power consumption for obtaining of fresh water in the amount of 42 l/h are composed of energy consumption of equipment such as ventilator, pump and compressor, and are determined by the formulas:

$$N_1 = P_V \cdot L / \eta_1 = 0{,}55 \cdot 1{,}00 / 0{,}75 = 0{,}73 \text{ kWh} = 2640 \text{ J}; \quad (1)$$

$$N_2 = G_W \cdot H / \eta_2 = 0{,}003 \cdot 200 / 0{,}7 = 0{,}86 \text{ kWh} = 3086 \text{ J};$$
$$N_3 = Q_C / \text{COP} = 48{,}0 / 5{,}0 = 9{,}6 \text{ kWh} = 34560 \text{ J};$$
$$\Sigma N = N_1 + N_2 + N_3 = 40286 \text{ J};$$

where N_1, N_2, N_3 – power of ventilator, pump and compressor respectively, kWh; P_V – full pressure of ventilator, kPa; L – air flow, m^3/sec; η_1, η_2 – efficiency of ventilator and pump respectively; H – pump pressure, kPa; G_W – salt water flow, m^3/sec; Q_C – cooling capacity of the chiller, kW; COP – refrigerating factor.

Calculations (1) show that the cumulative energy consumption for generating 1 l of desalinated water according to the proposed scheme taking into account a compressor, a ventilator and a pump do not exceed 1000 J, which is almost 2.5 times less than in traditional distillation units (2400 J without taking into account the pump).

4. Results

Virtually all the equipment which is used for the desalinator assembly, is not expensive since it is mass-produced by numerous companies. Combined with low energy consumption, simplicity of design and current maintenance, high reliability and environmental security this makes it possible to recommend the proposed desalination design option for mass production of individual desalinators of sea water and other types of salty waters.

Acknowledgments

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