Apparatus and Method for Improved Desalination

Field of invention

The invention relates to the desalination of saline or brackish water and includes the method for processing and enhancing the said water to produce water at low total dissolved solids.

Background

Desalination has been the practical solution to water shortage problem in many arid areas of the world. There are several methods for desalination and the desalination methods basically can be categorized into two groups: namely (i) thermally activated process, and (ii) electric power driven method. Thermal activated process mainly includes multi-stage flash desalination (MSF) and multi-effect desalination (MED). The second method includes reverse osmosis (RO), freezing, mechanical vapor compression and electro-dialysis. Hybrid plants, combining the RO and MSF processes can recover higher water yields of higher quality, typically the dissolved solids being less than 500 mg/l.

All of the aforementioned types of desalination have three fundamental drawbacks, being: (i) the high energy usage to maintain relatively high temperatures, typically exceeding 110°C, (ii) high energy intensive, and (iii) the high maintenance costs arising from salt deposition or fouling in the evaporating unit.

Statement of the invention

The object of the present invention is to reduce the energy requirement of desalination process as compared to the established processes found in the prior art.

In a first aspect, the invention provides a water desalination system comprising an evaporator for evaporating saline water to produce water vapor; a condenser for condensing the water vapor; wherein the evaporator and the condenser are in heat transfer communication such that heat used by the evaporator is at least in part derived from the condenser.

In a second aspect, the invention provides a process for desalinating water comprising the steps of evaporating saline water within an evaporator to produce water vapor; condensing the water vapor to form desalinated water; heating said evaporator using heat derived from the condensing step.

For embodiments whereby the evaporator and condenser remain heat transfer communication, the total internal heat regeneration in the adsorption desalination (AD) cycle may be performed by (i) a chamber that functions as an integrated evaporator-condenser where total internal heat regeneration is achieved, or (ii) heat-exchanging-medium circuit which transfers condensation energy and evaporation. In both cases, the heat derived from the condenser, and communicated to the evaporator give rise to an enhancement in the performances of the adsorption and desorption processes of the adsorption

cycle. It will be appreciated that other arrangements may also be used, which fall within the scope of the present invention.

With the use of an integrated evaporator-condenser unit, the improvement in the specific daily water production rate (SDWP), defined here as the amount of potable water produced per day by 1 tonne of adsorbent (silica gel), may increase up to three fold to as high as 35 m^3 of potable water per tonne of adsorbent material per day. In so doing electrical energy consumption may be as low as 1.5 kWh/m^3 or even lower. This is lower than conventional thermal or reverse osmosis plants according to the prior art.

In one embodiment, the integrated evaporator-condenser chamber is used for the evaporation of saline, brackish or waste water and the condensation of the water vapor where the required energy for evaporation is extracted from the condensation process of water vapors. External energy sources for evaporation or external cooling for condensation may not be required in the proposed design as the heat of condensation is used for the evaporation process of saline water. Nevertheless, in an alternative arrangement, additional heat sources may be used to supplement or substitute for the heat from the condensation.

In a further embodiment, the evaporation process may be enhanced by the energy rejected from the condenser resulting in higher system pressure for the adsorption and thus increased in adsorption capacity of the adsorbent. At the same time, the condensation process may also be boosted due to the extraction

of energy by the evaporation process. On the other hand the desorption process may also be improved because of the lower pressure condition. Therefore, the overall performance of the AD system may be boosted and the system yields higher water production rate.

In another embodiment, the adsorption means may include at least one array of adsorption beds, each bed comprising a quantity of adsorbent material such as silica gel or synthetic zeolite, or any other hydrophilic porous adsorbent with the possibly of having a surface area not less than 500 m^2/g.

In a further embodiment, each bed may be a finned-tube heat exchanger with the adsorbent material placed in interstitial spaces between the finned tubes or each bed may include a mesh adapted to encapsulate the heat exchanger so as to retain the adsorbent material.

In one embodiment, the energy requirement for evaporation may be recovered from the condensation heat, with the evaporator-condenser chamber employing as evaporation and condensation mechanisms. The evaporator cavity may communicate with the adsorbent material in the adsorber bed and the condenser cavity may communicate with the vapor-saturated desorber bed. The affinity of the adsorbent material in the adsorber bed initiates the evaporation of saline water and the vapors are adsorbed on the adsorbent material until the equilibrium state is reached. The water vapor in the saturated adsorbed bed may be driven out using low temperature hot water, for instance, less than 85°C.

The low temperature hot water may be attained either by solar energy or industrial waste heat. The driven out water vapors from the saturated bed may be condensed inside the condenser where the heat of condensation is utilized for evaporation.

In a further embodiment, the stainless steel-finned tubes may be arranged either horizontally or vertically in the evaporator-condenser chamber. The evaporation may be achieved by a pool boiling process and the energy for evaporation obtained from the condensation of the desorbed vapors inside the condenser where the condensation may be either film or drop wise..

In one preferred embodiment, the evaporation of the saline water may be enhanced by using spray nozzles. The temperature range of the evaporator may be 15 to 40°C and consequently the fouling of the evaporating unit may be lessened and thus results in lowering the maintenance cost of the plant.

In a further embodiment, the evaporator cavity of the evaporator-condenser chamber may communicate with a pretreatment chamber where the required pretreatment processes of the saline water are conducted. The condenser cavity of the evaporator-condenser chamber may also communicate with the collection chamber where the desalinated water is collected.

In one preferred embodiment, the number of adsorber beds may be at least two or more. The communication of the beds containing the adsorbent materials to

the evaporator cavity of the evaporator-condenser chamber may be in series or parallel.

In a further embodiment, the adsorber bed, desorber bed and evaporator-condenser chamber may be encapsulated in a single silo partitioned by a wall between them and the evaporator-condenser chamber so that the plant becomes more compact and portable.

In another embodiment, only the evaporator-condenser chamber may be made of anti-corrosive materials such as alloy steel to prevent corrosion. The rest components of the plant such as adsorber and desorber chamber can be made of conventional carbon steel or concrete.

In another embodiment, heat-exchanging medium circuit such as water loop connecting the condenser and evaporator of the AD plant exchanges condensation and evaporation energy. Only a small capacity pump is installed for the circulation by eliminating both the chilled water and cooling water pumps.

In a further embodiment the heat transfer conduit between the evaporator and condenser may include a plate. This plate may be of a material having greater thermal conductivity as compared to the materials used to construct the evaporator and/or condenser.

Brief Description of Drawings

It will be convenient to further describe the present invention with respect to the accompanying drawings which represent possible arrangements of the invention. Other arrangements of the invention are possible and consequently, the particularity of the accompanying drawings is not to be understood as superseding the generality of the proceeding description of the invention.

Figure-1 is a schematic view of the desalination system and process according to the present invention.

Figure-2 is the plan schematic view according to one embodiment of the present invention.

Figure-3 shows the simulated temperature-time histories of the adsorber and desorber bed and evaporation and condensation of the embodiment of the present invention.

Figure-4 is the predicted production rate of fresh water of the embodiment of the present invention.

Figure-5 is a schematic view of an AD cycle with heat recovery circuit according to a further embodiment of the present invention;

Figure-6 is a comparison on SDWP of a system of Figure-5 to a conventional cycle

Description of Preferred Embodiment

Figure-1 shows the schematic view of the desalination system, according to one embodiment, comprising an evaporator/condenser chamber and two reactor bed containing adsorbent materials. Saline or brackish water is evaporated inside the evaporator chamber 3. The energy for evaporation is extracted from the condensation of the vapors inside the condenser chamber 4. Whilst in this embodiment a significant proportion of the heat used by the evaporator is derived from the condenser, in other embodiments, within the present invention, varying degrees of heat may be used.

Further whilst in this embodiment the evaporator is substantially located within the condenser in order to better derive said heat, the invention encompasses other means of transferring said heat such as the evaporator and condenser sharing a heat transfer conduit. This may include a common wall, such as a plate, with heat dissipation arrangements, including fins, in order to better transfer the heat from the condenser to the evaporator. Whilst in the embodiment shown in Figure 1 there may be advantages in utilizing all of the heat generated by the condenser, in the latter described embodiment there may be advantage in using externally applied heat sources to the evaporator. It will be appreciated that the specific arrangements of the evaporator and condenser will be determined by the skilled person and designed according to specific applications, all of which fall within the present invention.

It will be further appreciated that the present invention is applicable to a range of different desalination systems and represents an increased efficiency which will provide a beneficial result when applied to said systems. One such system is disclosed in WO2006/121414, the contents of which are incorporated herein by reference. It will be noted that the present invention is not limited to its application to this type of desalination system. Nevertheless the application of the present invention to aspects of the system described by WO 2006/121414 provides an example of how the present invention may be applied to a desalination system. Alternative arrangements will equally fall within the present invention.

The process according to a further embodiment of the present invention is fundamentally a batch process comprising of two stages. The first stage being the adsorption phase, involves the water vapor being directed to the adsorber beds for a predetermined time. This predetermined time may be a function of the saturation capacity of the adsorbent material or alternatively subject to achieving the most effective or efficient process either economically or production-wise. The water vapors from the evaporator passes through the vapor pipe line 5 and butterfly valve 6 that is electro-pneumatically controlled and are adsorbed on the adsorbent inside the adsorber chamber 1. An external cooling circuit 7 is used to reject the heat of adsorption from the adsorption process. During adsorption process, solenoid water valves 14 are opened to allow the flow of the cooling water through the adsorber tube. The adsorption process continues until the adsorbent materials inside the adsorber bed are fully

saturated with vapors. The gas valve 6 communicating the evaporator and the adsorber bed are closed when the adsorbent materials inside the adsorber chamber are fully saturated with water vapors. The water valves 14 that direct the cooling water flow to the adsorber chamber are also closed and the hot water valves 13 open letting the flow of hot water through the hot water pipe line 8. This process is known as switching process and the switching action increase the pressure of the adsorber bed to condensing pressure. This length of the switching time may vary depending on the hot water temperature and hot water flow rate. After the switching period, the gas valve 10 communicating the adsorber chamber and the condenser chamber is opened. The desorption process is achieved by the flow of hot water through the hot water pipe line 8 while the solenoid or electro-pneumatic controlled hot water valves 13 direct the flow of hot water through the adsorber chamber. The desorbed water vapors from the adsorber bed travels through the desorber pipe line 9 and the solenoid or electro-pneumatic controlled gas valve 10 and are condensed inside the condenser chamber 4 of the evaporator/condenser chamber. The condensation process is maintained by rejecting the heat of condensation to the evaporation process of the saline water inside the evaporator 3. The condensate inside the condenser 4 of the evaporator chamber is collected using a U-tube 11 to maintain the pressure difference between the condenser 4 that is at vacuum pressure and the fresh water collection tank 12 whose pressure is about atmospheric pressure. The collection of the fresh water from the condenser also includes other means such as using water pumps etc. Whilst not essential to the invention, the process according to the present invention is made more

efficient, and so increase water production, through cooling the array of adsorbent beds during the adsorption phase and heating of the array of adsorbent beds during the desorption phase.

Describing in more detail the cooling and hot water supplies, the cooling water is circulated from a cooling tower (not shown), whereby the collected heat from the adsorption phase is dissipated to the environment. The re-cooled water is then returned to the common cooling water line 7 for distribution to the appropriate reaction bed tower in the adsorbent material. It should be noted that, for a range of purpose, it may be preferable to only re-circulate a portion of the cooling water. The non -circulated water may be dumped, used for a different system. Most water production sizes of the commercial scale desalination plants are of the order of million gallons per day (MGD). One alternative falling within the present invention is to have modular design for the reactor towers, as proposed in Figure-1.

A 200 tonne capacity of adsorbent per "Silo" type tower may have a diameter of 4 to 5 m and a height of 25 m, as shown in Figure-1. Figure 5 gives the advanced adsorption desalination cycle 52 with energy recovery circuit from the condenser 55 and evaporator 60. Only a small capacity pump 58 is required to drive the circulation of the water that exchanges condensation heat and evaporation heat. This invention eliminates the two high-capacity condenser water and chilled water pumps.

Mathematical model

The energy balance equations, the isotherm equations and the kinetic equation for the AD system are presented below.

The Tóth equation (1) is used to calculate the amount of water vapor adsorbed at specific temperature and pressure of the adsorbent.

$$q^* = \frac{K_0 . \exp(\Delta H_{ads} / RT) . p}{[1 + (K_0 / q_m . \exp(\Delta H_{ads} / RT) . p)^r]^{1/r}} \quad (1)$$

To estimate the transient amount of adsorbed and desorbed water vapor, the following kinetic equation (2) is used.

$$\frac{dq}{dt} = \frac{15 D_{so} \exp(-E_a / RT)}{R_p^2} (q^* - q) \quad (2)$$

Energy balance for the adsorption and desorption

Equation (3) gives the energy balance equation for the adsorption and desorption process of the AD system.

$$\rho c_p \frac{dT_{ads/des}}{dt} = m_{sg} \Delta H_{ads} \frac{dq}{dt} \pm \dot{m}_{cw/hw} C_p (T_{cw/hw}(in) - T_{cw/hw}(out)) \quad (3)$$

Energy balance for the evaporation and condensation

The evaporation of salt water in the evaporator cavity is achieved by pool boiling process and the heat transfer coefficient of evaporation is calculated using **Modified Rohsenow correlation for sub-atmospheric pressures** (4) (Ng et. al, Applied Thermal Engineering, 26 (2006) 1286–1290) follow.

$$T_w - T = \left(\frac{C_{sf} h_{fg} \Pr_l^s}{C_{pl}}\right)\left[\frac{q''_{load}}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}\right]^n \times \left(\frac{P}{P_{atm}}\right)^m \left(\frac{A_{wetted}}{A_{base}}\right)^\alpha \qquad (4)$$

Nusselt film correlation is applied to calculate the heat transfer coefficient for condensation and it is given in equation (5).

$$h = F\left[\frac{\rho_l g k^3 (\rho_l - \rho_v)[h_{fg} + \frac{3}{8} C_{pl}(T - T_w)]}{D\mu(T - T_w)}\right]^{\frac{1}{4}} \qquad (5)$$

Simulation results

The simulation of the AD cycle is done by using FORTAN IMSL library function. A set of modeling differential equations are solved by using Gear's BDF method. The parameters used in the simulation are listed in the following table.

	Temperature (°C)	Flow rate (LPM)
Hot water inlet (desorber)	85	48
Cooling water inlet (adsorber)	29.5	48
Mass of silica gel per bed (kg)	36	
Cycle time (s)	300	
Switching time (s)	20	
Number of tubes for condensation	60	
$A_{evaporator}$	9.34	
$A_{condenser}$	5.353	

Figure-3 shows the temperature-time histories of the adsorption 20, desorption 30 evaporation 50 and condensation 40 of the preferred embodiment. The amount of fresh water production rate in terms of specific daily water production (SDWP) is shown in Figure-4 and the predicted SDWP is 27 m^3 of fresh water per tonne of silica gel per day.

Experimental results

A heat-exchanging circuit, here we used water circuit, connecting the evaporator and condenser of the AD plant is installed on the prototype AD plant. The experiments are conducted using hot water temperature at 80°C and cycle time 1200s. The enhancement attributed by the current invention is presented

by comparing the water production rate of the advanced cycle and conventional cycle in Figure-5. The increment in SDWP of the advanced AD chiller with heat recovery circuit between condenser and evaporator compared to that of conventional cycle is more than 75%, as can be seen from the graphical representation of Figure-6.

CLAIMS

1. A water desalination system comprising:

an evaporator for evaporating saline water to produce water vapor;

a condenser for condensing the water vapor;

wherein the evaporator and the condenser are in heat transfer communication such that heat used by the evaporator is at least in part derived from the condenser.

2. The water desalination system according to claim 1, wherein said evaporator and condenser are arranged in an integrated unit.

3. The water desalination system according to claim 1 or 2 wherein the evaporator is at least partially enclosed by the condenser.

4. The water desalination system according to claim 1 or 2 wherein the said evaporator and condenser are positioned adjacent to each other having a heat transfer conduit placed intermediate to the said evaporator and condenser.

5. The water desalination system according to claim 4 wherein the heat transfer conduit includes a plate coupled to both the evaporator and condenser said plate having a greater thermal conductivity than other portions of the evaporator and condenser.

6. The water desalination system according to claim 4 or 5 wherein the evaporator is in heat transfer communication with other heat sources.

7. The water desalination system according to any one of claims 1 to 6, further including:

an adsorption means in selective vapor communication with the evaporator for reversibly adsorbing the water vapor from the evaporator;

said adsorption means in selective vapor communication with the condenser, and;

desorbing means for desorbing the adsorbed water vapor from the adsorption means for collection by the condenser.

8. The system according to claim 7, wherein the adsorption means includes at least one array of adsorption beds, each bed comprising a quantity of adsorbent material.

9. The system according to claim 8, wherein each bed includes a finned-tube heat exchanger, said adsorbent material placed in interstitial spaces between said finned tubes.

10. The system according to any one of claim 7 to 9, wherein the adsorption means includes a cooling means proximate to the array of

beds for cooling each bed to aid in the adsorption of the water vapour.

11. The system according to claim 10, wherein said cooling means comprises cooling water circulation system for circulating cooling water to the heat exchangers.

12. The system according to claim 11, wherein the cooling water circulation system re-circulates at least a portion of the cooling water from the heat exchangers back to the cooling tower.

13. The system according to any one of claims 10 to 12, wherein the cooling means further includes a chilled water circulation system for circulating chilled water to the heat exchangers.

14. The system according to claim 13, wherein the chilled water is sourced from the evaporator.

15. The system according to claim 14, wherein the chilled water circulation system re-circulates the chilled water from the heat exchangers back to the evaporator.

16. A process for desalinating water comprising the steps of :

evaporating saline water within an evaporator to produce water vapor;

condensing the water vapor to form desalinated water;

heating said evaporator using heat derived from the condensing step.

17. The process for desalinating water according to claim 16, further comprising the steps, after the evaporating step, of:

reversibly adsorbing the water vapor from the evaporator using an adsorption means in selective vapor communication with the evaporator, and;

desorbing the adsorbed water vapor from the adsorption means using the desorbing means and delivering the water vapor to the condenser.

18. The process according to claim 17, wherein the evaporating and adsorbing steps are performed until saturation of the adsorption means, whereupon the vapor communication between the adsorption means and the evaporator is selectively disengaged, and the desorbing and condensing steps commenced until a substantial quantity of the adsorbed water vapour has been desorbed from the adsorption means, said vapour communication subsequently re-engaged.

19. The process according to claims 17 or 18, wherein the adsorbing step includes circulating cooling water proximate to an array of adsorption for cooling each bed to aid in the adsorption of the water vapor.

20. The process according to any one of claims 17 to 19, wherein the adsorbing step further includes circulating chilled water proximate to the array of beds for chilling each bed to aid in the adsorption of the water vapor.

21. The process according to claims 19 or 20, wherein the desorbing step includes circulating hot water proximate to the array of beds for heating each bed to aid in the desorption of the adsorbed water vapor.