SYSTEM AND METHOD FOR SORBTION DISTILLATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 15/637,236, filed on Jun. 29, 2017. This application also claims benefit of U.S. Patent Application No. 62/356,126, filed Jun. 29, 2016, which is hereby incorporated in its entirety by reference.

BACKGROUND

[0002] Population growth, increasing precipitation variability from climate change, and aquifer depletion will result in water stress for over half the world population, >5 billion people, by 2050 (see C. A. Schlosser et. al., "The Future of Global Water Stress: An Integrated Assessment," MIT, Cambridge, Mass., MIT Joint Program on the Science and Policy of Global Change 254, 2014.). Desalination capacity is growing globally and within the US as water usage exceeds natural capacities. Grid-powered reverse osmosis (RO) is currently the most favored technology, but requires electricity, which remains mostly fossil-based.

[0003] Many review papers have been published comparing conventional and advanced desalination (see O. K. Buros, The ABCs of Desalting: International Desalination Association, 2000; O. A. Hamed, "Overview of hybrid desalination systems–current status and future prospects," Saline Water Conversion Corporation (SWCC), Al-Jubail, Saudi Arabia, 2004; M. T. Ali et. al., "A comprehensive techno-economical review of indirect solar desalination,"; Renewable and Sustainable Energy Reviews, vol. 15, pp. 4187-4199, 2011; J. E. Miller, "Review of Water Resources and desalination technologies," Sandia National Laboratories, Albuquerque, N. Mex., SAND Report 2003-0800, 2003; S. Chaudhry. (2012, October) New and Emerging Desalination. http://www.iapws.org/minutes/2012/Symp-Chaudhry.pdf; J. Tonner, "Barriers to thermal desalination in the United States," U.S. Department of the Interior Bureau of Reclamation, Denver, Colo., Desalination and Water Purification Research and Development Program Report 144, 2008.)

[0004] Miller's 2003 SAND report succinctly describes the challenges of thermal processes: "All thermal distillation processes have one notable Achilles Heel, and that is the large amount of energy it takes to evaporate water (about 2200 kJ/kg) compared to the theoretical minimum energy required for desalination (3-7 kJ/kg)". Mechanical energy is easier to reuse, therefore reverse osmosis has become the most competitive desalination technique. The largest desalination plant being built in the US, the San Diego Carlsbad plant [Carlsbad Desalination Project, "Energy minimization and greenhouse gas reduction plan," San Diego, Calif., 2008], uses RO and achieves an estimated energy intensity of 3.6 kWh_e/m^3 (13 kJ_e/kg) after upgrades to state-of-the-art pressure exchangers.

[0005] Conventional thermal desalination techniques such as multiple-effect distillation (IVIED) and multi-stage flash (MSF) plants have been limited to gained output ratio (GOR/PR) of around 10 for several decades. The gained output ratio (GOR) is the ratio of input steam mass to product water mass. It is equivalent to the performance ratio (PR) which is kg of product water per 2326 kJ or lbs. of product water per 1000 BTUs. Simple single stage distillation would have a GOR or PR of 1. Improvements to the efficiency of these pure thermal cycles have come from using higher exergy energy to recycle low temperature latent heats. High pressure steam drives thermal vapor compression (TVC) and mechanical energy is used in mechanical vapor compression (MVC). However, these techniques incorporate power generation equipment to convert thermal energy to higher exergy input. Desalination using electrical or mechanical energy can seem more efficient as they outsource thermal losses to the energy conversion process. For example, Dean Kamen's Slingshot is a MVC distiller with an energy intensity of 24 kWh_e/m^3, but generates electricity using a 15% efficient Sterling engine (see S. L. Nasr. Howstuffworks. http://science.howstuffworks.com/environmental/green-tech/remediation/slingshot-water-purifier2.htm).

[0006] Solar thermal desalination faces challenges on two fronts: reducing energy intensity and collecting solar energy cost effectively. There would be immense benefit if direct solar-powered desalination could be made cost-competitive with grid-powered reverse osmosis.

[0007] A rapidly deploying, portable, and dynamically sized desalinator can significantly reduce the risk of stranded cost and barriers to entry. At 16,000 gallons per day (gpd) for each unit, a 1 Mgpd plant composed of 63 units could be transported across the US by a single train. Compared to current long lead-time desalination plants, time to water production could be reduced from a decade to weeks.

SUMMARY OF THE INVENTION

[0008] Disclosed is a distillation system, comprising a heat source and a plurality of open-cycle adsorption stages, each stage comprising a plurality of beds; and an evaporator and a condenser between a first stage hot adsorbent bed and a first stage cold adsorbent bed. In this embodiment, each bed comprises at least two vapor valves switching vapor flow between each bed and either the condenser or evaporator of the same stage, a plurality of hollow tubes, a plurality of channels adapted to facilitate water vapor flow between either the condenser or the evaporator and the bulk of either of the adsorbent beds. Each adsorbent bed is composed of a porous media, a hygroscopic material, and a plurality of graphite flakes.

[0009] Also disclosed is a method for distilling water. This method utilizes a plurality of stages, each stage comprising a hot adsorbent bed and a cold adsorbent bed, and functions by repeating cycles of a forcing phase followed by a relaxing phase. The forcing phase comprises the steps of providing a heat source to heat the hot bed of a first stage to a first temperature, desorbing water vapor from the hot bed of the first stage and flowing the water vapor into a first condenser, condensing water vapor in the first condenser to form a liquid water and removing at least some of the liquid water from the first condenser, providing a solution comprising water and at least one dissolved impurity to a first evaporator, transferring the latent heat from the first condenser to the first evaporator to partially evaporate the solution comprising water and at least one dissolved impurity to form water vapor and providing the remaining more concentrated solution to an evaporator of a subsequent stage, adsorbing water vapor from the first evaporator into the cold bed of the first stage, and transferring the heat of adsorption generated by the cold bed of the first stage to heat a hot bed of a second