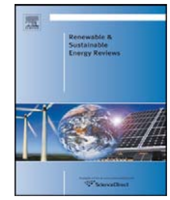
Renewable and Sustainable Energy Reviews 14 (2010) 1187–1201

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production

G. Prakash Narayan [a], Mostafa H. Sharqawy [a], Edward K. Summers [a], John H. Lienhard [a,*], Syed M. Zubair [b], M.A. Antar [b]

[a] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, USA
[b] Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, Saudi Arabia

ARTICLE INFO

Article history:
Received 25 May 2009
Received in revised form 4 November 2009
Accepted 7 November 2009

Keywords:
Humidification
Dehumidification
Desalination
Decentralized water production
Solar power
Small-scale water production

ABSTRACT

World-wide water scarcity, especially in the developing world, indicates a pressing need to develop inexpensive, decentralized small-scale desalination technologies which use renewable resources of energy. This paper provides a comprehensive review of the state-of-the-art in one of the most promising of these technologies, solar-driven humidification–dehumidification (HDH) desalination. Previous studies have investigated many different variations on the HDH cycle. In this paper, performance parameters which enable comparison of the various versions of the HDH cycle have been defined and evaluated. To better compare these cycles, each has been represented in psychometric coordinates. The principal components of the HDH system are also reviewed and compared, including the humidifier, solar heaters, and dehumidifiers. Particular attention is given to solar air heaters, for which design data is limited; and direct air heating is compared to direct water heating in the cycle assessments. Alternative processes based on the HDH concept are also reviewed and compared. Further, novel proposals for improvement of the HDH cycle are outlined. It is concluded that HDH technology has great promise for decentralized small-scale water production applications, although additional research and development is needed for improving system efficiency and reducing capital cost.

Contents

* Corresponding author. Tel.: +1 617 253 3790.
E-mail address: lienhard@mit.edu (J.H. Lienhard).

1364-0321/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2009.11.014

1. Introduction

The Millennium development goals set by the United Nations highlight the critical need of impoverished and developing regions of the world to achieve self-sustenance in potable water supply [1]. Desalination systems are essential to the solution of this problem. However, conventional desalination technologies are usually large-scale, technology intensive systems most suitable for the energy rich and economically advanced regions of the world. They also cause environmental hazards because they are fossil-fuel driven and also because of the problem of brine disposal. In the following sections these conventional desalination technologies are introduced and their drawbacks are discussed.

1.1. Conventional desalination technologies

Desalination of seawater or brackish water is generally performed by either of two main processes: by evaporation or by use of a semi-permeable membrane to separate fresh water from a concentrate. The most important of these technologies are listed in Table 1. In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a heat source. The heat source may be obtained from a conventional fossil-fuel, nuclear energy or from a non-conventional source like solar energy or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for establishing electric fields to separate the ions.

The most important commercial desalination processes [2] based on thermal energy are multi-stage flash (MSF) distillation, multiple effect distillation (MED) and vapor compression (VC), in which compression may be accomplished thermally (TVC) or mechanically (MVC). The MSF and MED processes consist of many serial stages at successively decreasing temperature and pressure. The MSF process is based on the generation of vapor from seawater or brine due to a sudden pressure reduction (flashing) when seawater enters an evacuated chamber. The process is repeated stage-by-stage at successively decreasing pressures. Condensation of vapor is accomplished by regenerative heating of the feed water. This process requires an external steam supply, normally at a temperature around 100 °C. The maximum operating temperature is limited by scale formation, and thus the thermodynamic performance of the process is also limited. For the MED system, water vapor is generated by heating the seawater at a given pressure in each of a series of cascading chambers. The steam generated in one stage, or "effect," is used to heat the brine in the next stage, which is at a lower pressure. The thermal performance of these systems is proportional to the number of stages, with capital cost limiting the number of stages to be used. In TVC and MVC systems, after vapor is generated from the saline solution, it is thermally or mechanically compressed and then condensed to generate potable water.

Table 1
Desalination processes.

Phase-change processes	Membrane processes
1. Multi-stage flash (MSF)	1. Reverse osmosis (RO)
2. Multiple effect distillation (MED)	2. Electrodialysis (ED)
3. Vapor compression (VC)	
4. Solar stills	

The second important class of industrial desalination processes uses membrane technologies. These are principally reverse osmosis (RO) and electrodialysis (ED). The former requires power to drive a pump that increases the pressure of the feed water to the desired value. The required pressure depends on the salt concentration of the feed. The pumps are normally electrically driven [3]. The ED process also requires electricity to produce migration of ions through suitable ion-exchange membranes [4]. Both RO and ED are useful for brackish water desalination; however, RO is also competitive with MSF distillation processes for large-scale seawater desalination.

The MSF process represents more than 90% of the thermal desalination processes, while RO process represents more than 80% of membrane processes for water production. MSF plants typically have capacities ranging from 100,000 to almost 1,000,000 m^3/day [5]. The largest RO plant currently in operation is the Ashkelon plant, at 330,000 m^3/day [6].

Other approaches to desalination include processes like the ion-exchange process, liquid–liquid extraction, and the gas hydrate process. Most of these approaches are not generally used unless when there is a requirement to produce high purity (total dissolved solids <10 ppm) water for specialized applications.

Another interesting process which has garnered much attention recently is the forward osmosis process [7]. In this process, a carrier solution is used to create a higher osmotic pressure than that of seawater. As a result the water in seawater flows through the membrane to the carrier solution by osmosis. This water is then separated from the diluted carrier solution to produce pure water and a concentrated solution which is sent back to the osmosis cell. This technology is yet to be proven commercially.

1.2. Limitations of conventional technologies

Conventional processes like MSF and RO require large amounts of energy in the form of thermal energy (for MSF) or electric power (for RO). Most desalination plants using these technologies are fossil-fuel driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil. To avoid these issues, desalination technologies based on renewable energy are highly desirable.

Solar energy is the most abundantly available energy resource on earth. Solar desalination systems are classified into two main categories: direct and indirect systems. As their name implies, direct systems use solar energy to produce distillate directly using the solar collector, whereas in indirect systems, two sub-systems are employed (one for solar power generation and one for desalination). Various solar desalination plants in pilot and commercial stages of development were reviewed by [8].

In concept, solar energy based MSF and MED systems are similar to conventional thermal desalination systems. The main difference is that in the former, solar energy collection devices are used. Some proposals use centralized, concentrating solar power at a high receiver temperature to generate electricity and water in a typical large-scale coproduction scheme [9]. These solar energy collectors are not yet commercially realized. It should be noted that at lower operating temperatures, solar collectors have higher collection efficiency, owing to reduced losses, and also, can be designed to use less expensive materials.