An overview of solar thermal desalination technologies

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Abstract: - Solar energy has a very promising role to play in addressing water scarcity problems through thermal desalination processes around the world. Direct solar desalination uses solar energy to produce distillate directly in the solar collector whereas indirect solar desalination combines conventional desalination techniques, such as multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis with solar collectors for heat generation. This paper describes several desalination technologies which could be integrated into solar thermal energy systems.

Keywords: Solar energy, solar thermal desalination, solar stills

1 Introduction

Desalination is defined as a process of removing dissolved minerals from feedwater sources such as seawater, brackish water or treated wastewater in order to improve the taste or properties of the water. The lack of drinking water is an acute problem that exists in arid regions of the world where fresh water is becoming very scarce and costly. Potable water is one of the most important international health issues today and large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. Even today, one fourth of mankind is suffering from inadequate fresh water supply [1]. Globally, the total installed capacity of desalination plants was 71.9 million m^3 per day in 2012 [2]. Seawater desalination accounts for 67% of production, followed by brackish water at 19%, river water at 8%, and wastewater at 6%. Figure 1 shows the worldwide feed-water percentage used in desalination [3].

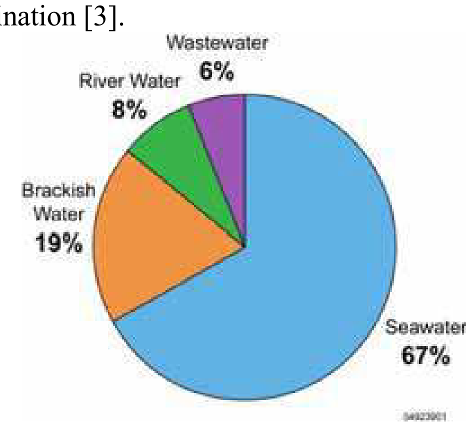

Figure 1: Worldwide feed-water percentage used in desalination

Desalinated water is most abundantly used in Middle Eastern Arab countries, namely, Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Oman, and Bahrain [4]. The technology for desalination can be classified into three major categories, as follows:

- Process based on a physical change in state of the water – i.e. distillation or freezing
- Process using membranes – i.e. reverse osmosis or electrodialysis, and
- Process acting on chemical bonds – i.e. ion exchange.

Of the above processes, those based on chemical bonds, such as ion exchange, are mainly used to produce extremely high quality water for industrial purposes and are not suitable for treating seawater or brackish water. The other two processes are regularly used to treat seawater and brackish water and have been developed over many years in large scale commercial applications. The major processes of desalination are therefore membrane and distillation processes.

Figure 2 shows a simplified diagram of a desalination system. Raw feedwater is pre-treated prior to entering one or more parallel desalination process trains. There are 3 process trains in this figure. Desalted product water undergoes post-treatment, as required for the application, and is pumped to the distribution system. The salts and other residuals separated out of the feedwater in the desalination process are continuously discharged to waste as concentrate.

A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. This process requires some form of energy to desalinate, and utilizes several different technologies for separation. A variety of desalination technologies has been developed over the years on the basis of thermal distillation, membrane separation, freezing, electrodialysis, etc [5, 6].

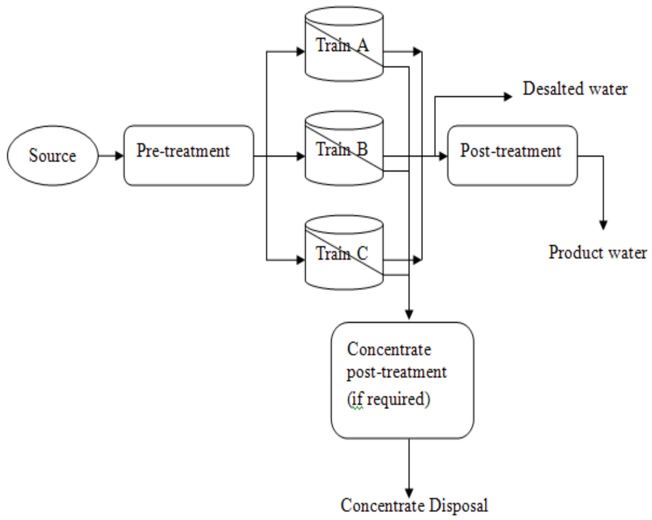

Figure 2: Schematic of overall process of desalination

Solar energy can directly or indirectly be used for desalination. There are two types of collection systems: Direct desalination systems are collection systems that use solar energy to produce distillate directly in the solar collector whereas indirect systems combine solar energy collection systems with conventional desalination systems. In indirect systems, solar energy is used either to generate the heat required for desalination and/or to generate electricity that is used to provide the required electric power for conventional desalination plants such as multi-effect (ME), multi-stage flash (MSF) or reverse osmosis (RO) systems [7]. The recent developments in solar thermal desalination technologies are discussed in this paper.

2 Solar thermal desalination technologies

The existing solar thermal desalination technologies are described and discussed below.

2.1 Direct solar desalination

The method of direct solar desalination is suitable for small production systems, such as solar stills, in regions where the freshwater demand is less than 200 m^3/day [8]. This low production rate is due to the low operating temperature and pressure of the steam. The simple solar still of the basin type is the oldest method and improvements in its design have been made to increase its efficiency [9]. A single-effect solar still is a simple device which can be used to convert saline, brackish water into drinking water. In Solar stills a transparent cover encloses a pan of saline water which traps solar energy within the enclosure. This heats up the water causing evaporation and condensation on the inner face of the sloping transparent cover. This distilled water is generally potable; the quality of the distillate is very high because all the salts, inorganic and organic components and microbes are left behind in the bath.

Under reasonable conditions of sunlight the temperature of the water will rise sufficiently to kill all pathogenic bacteria anyway. A film or layer of sludge is likely to develop in the bottom of the tank and this should be flushed out as often as necessary. Solar still has an average daily yield of 4-5 L/m^2/day after losses. Currently state-of-the-art single-effect solar stills have an efficiency of about 30–40% [10]. One of the main drawbacks of this type of desalination plant is the low thermal efficiency and productivity. This could be improved by various passive and active methods. These modifications are described briefly, as follows.

2.2 Modifications using passive methods

2.2.1 Basin stills

The operating performance of a simple basin type passive still can be increased by the following techniques,

- Still with black dye: Injecting black dye in the seawater increases the distillate yield [11].
- Still with additional condenser: Fath [11] found that adding a passive condenser in the shaded region of a single slopped still increases the still efficiency by 45%.
- Single slope versus double slope basin stills: Single slope still gave better performance than a double slope still under cold climatic conditions while the opposite is true under summer climatic conditions [12].
- Still with cover cooling: Increasing the temperature difference between the basin (heat source) and the cover (heat sink) lead to increase the water evaporation rate [13]. In stills with cover cooling, cooling water or saline solution is fed in the gap of a double glass cover to maximize the temperature difference. The cost, as such, is increased.

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2.2.2 Wick stills

In a wick still, the feed water flows slowly through wick (a porous, radiation-absorbing pad). Wick stills have two distinct advantages over basin stills. Firstly, the wick can be tilted so that the feed water presents a better angle to the sun reducing reflection and presenting a large effective area. Secondly, there is less feed water in the still at any time and therefore water is heated more quickly and to a higher temperature. Tanaka *et al.* have proven superiority of the tilted wick type solar still and confirmed an increase in productivity by 20–50% [14].

2.2.3 Diffusion stills

Diffusion solar stills consist of two separate units. One is a hot storage tank, coupled to a solar collector, and the other is the distillation unit, which produces the distilled water. Four-effect still is one of the most recent designs of this type of still [15]. The evaporation process in a four-effect still for the desalination of sea and brackish water was experimentally investigated in a test facility under different modes and configurations of heat recovery, and natural or forced convection in the four distillation chambers ("effects"). The theoretical distillate output from a 4-effect distillation unit was 8.7 kg/ m^2/ h with an energy input of 2.0 kW/m^2 under experimental conditions [16].

2.2.4 Solar still greenhouse combination

The Seawater Greenhouse combines a solar desalination system with an environment for cultivating crops in which transpiration is minimized, at the same time producing sufficient water for its own use through a process of solar distillation. Integrated design of greenhouses combined with solar stills represents an interesting possibility for the development of small-scale cultivation in places where only saline water or brackish water is available [12]. Chaibi constructed and analysed this system [17], where the south slope of the greenhouse roof was built as a solar still. Saline water was pumped from a reservoir to the rooftop of the greenhouse, from where it was distributed evenly to the evaporation surface in the still during the day. The top cover of the still was a regular glass sheet, while the bottom of the solar still composed of an only partly light transparent material, which absorbed a substantial amount of the solar irradiation, but transmitted wavelengths that are favourable for photosynthesis of vegetation (the photosynthetic active radiation (PAR) has the wavelength interval 380–710 nm). As still absorbed most of the heat radiation, therefore the temperature of the greenhouse air was lowered, resulting in a better climate for the crops and less ventilation requirement. Which eventually lead to a decrease in the water consumption of the crops [17].

2.2.5. Multiple-effect basin stills

Multiple-effect basin stills consist of two or more compartments. The condensing surface of the lower compartment is the floor of the upper compartment. The condensing vapor provides heat energy to vaporize the feed water. Multiple-effect solar desalination systems are more productive than single effect systems due to the fact that it reuses the latent heat of condensation. The increase in efficiency, though, must be counterpoised against the increase in capital and operating costs. Typical efficiency of these stills is 35% or more, which is greater than a single basin still but the cost and complexity are correspondingly higher. The desalination unit consists of a solar collector and a desalination tower made of six stages with a water circulation system to avoid salt accumulation in the tower. The production rate of the unit can reach 25 L/m^2/day for a value of 4.8 kW h/m^2/day of solar radiation [16].

2.2.6 Externally heated (active) solar stills

The temperature of saline water in the basin can be increased through additional external heating. For this purpose the still can be integrated with a

(a) solar concentrator
(b) solar heater
(c) waste heat recovery system

Water circulation through the heater or the concentrator could either be through natural circulation (Thermosyphon) or through forced circulation using a pump.

2.3 Water desalination with humidification–dehumidification (HD)

This process utilizes the principle of mass diffusion and uses dry air to evaporate saline water, thus humidifying the air. The HD process is based on the fact that air can be mixed with significant quantities of vapour. One of the problems that badly affect the still performance is the direct contact between the collector and the saline water; this may cause corrosion and scaling in the still and thereby reduce the thermal efficiency [18]. In HD desalination air is used as a working fluid, which eliminates this problem.

A temperature increment enhances the vapour carrying capacity of air i.e. 1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature increases from 30 to 80°C [16]. Freshwater is produced by condensing out the water vapor, resulting in dehumidification of the air. A significant advantage of this type of technology is that it provides a means for low pressure, low temperature desalination that can operate off waste heat and is potentially very cost effective. The principle of MEH plants is the distillation under atmospheric conditions by an air loop saturated with water vapor. The air is circulated by natural or forced convection (fans). The evaporator–condenser combination is termed a "humidification cycle", because the airflow is humidified in the evaporator and dehumidified in the condenser.

2.4. Multi-stage flash (MSF) process

MSF process is a water desalination process that distils sea water by flashing a portion of the water into steam in multiple stages of what are essentially counter current heat exchangers as shown in Figure 2. MSF produces 85% of all desalinated water in the world [19].

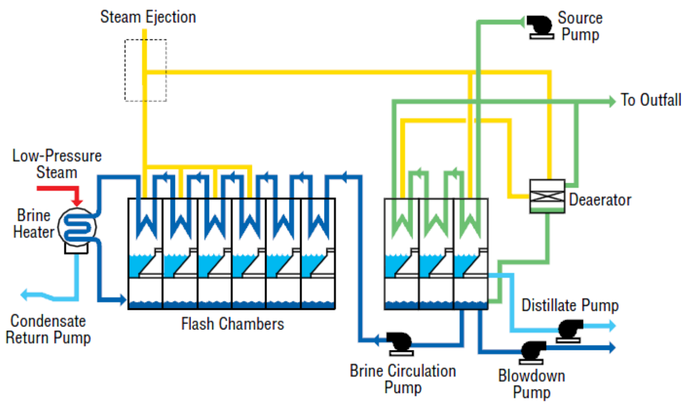

Figure 2: Multi stage flash process [20]

Block found that solar-powered MSF plants can produce 6–60 L/m^2/day, in comparison with the 3–4 L/m^2/day typical of solar stills [21]. The most commonly used type of solar collectors is salinity gradient solar ponds, and the parabolic trough collector, which is used in i.e. a MSF desalination plant in Kuwait for a production rate of 100 m^3/day [8].

2.5. Multiple-effect distillation

Multiple-effect distillation (MED), as shown in Figure 3, is the low temperature thermal process of obtaining fresh water by recovering the vapour of boiling sea water in a sequence of vessels, (called effects) each maintained at a lower temperature than the last. Because the boiling point of water decreases as pressure decreases, the vapour boiled off in one vessel can be used to heat the next one, and only the first one (at the highest pressure) requires an external source of heat [19] as shown in Figure 3 [19].

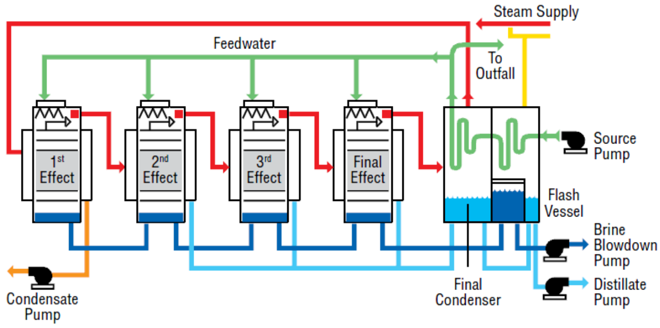

Figure 3: Multiple-effect Distillation process [20]

Many multiple-effect distillation (MED) plants of medium capacity powered by solar energy have been built worldwide. The small-scale MED desalination plant is a simple prototype small scale solar desalination system which consists of a tower with series of flat trays for effects and used a flat plate solar collector with oil as a heating medium for thermal energy [22]. Oil is circulated by natural convection between the solar collector and the first effect. The vapor from the first stage condenses at the bottom wall of the second stage, releasing it's latent heat. The condensed water moves through a channel to be collected outside the unit.

2.6 Freezing

Freeze distillation is a process of enriching a solution by partially freezing it and removing frozen material that is poorer in the dissolved material than is the liquid portion left behind. The concept is appealing in theory because the minimum thermodynamic energy required for freezing is less than for evaporation since the latent heat of fusion of water is 6.01 kJ/mole while the latent heat of vaporization at 100°C is 40.66 kJ/mole. Freezing has some advantages over distillation i.e. a lower theoretical energy requirement, minimal potential for corrosion and little scaling or precipitation. The disadvantage is that it involves handling ice and water mixtures that are mechanically complex to move and process. Despite the process advantage, freezing has not established itself as a commercial desalination technique because of the cost and complications of refrigeration systems and the need for freshwater to wash the crystals prior to melting. There are many designs of freeze separation processes as there are methods of refrigeration. The most commonly used methods are: vacuum freezing, vapour compression, ejector-absorption, and refrigeration freezing and secondary refrigerant.

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3 Further study

Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe. Further study should be carried out on the technological advancement of the various state-of-art hybrid desalination systems powered by solar thermal energy. Numerical modelling and design of an innovative solar thermal powered small to medium scale desalination prototype plant could be highly efficient and cost effective system for seawater/brackish water desalination. Authors are currently undertaking a project on Feasibility of Solar Desalination Plant at Central Queensland University (CQUniversity), Australia at their Rockhampton campus. The desalination of waste water being drained to ponds/lakes, rain water collected at ponds and salty underground water will be investigated as a future source of potable water supply to CQU network in order to assess whether the current water costs of CQUniversity can be reduced. The tasks that will be undertaken are to:

- Detail the quantity and quality of the feed water and indicate the expected variation in feed water quality parameters. In particular consideration should be given to salinity (TDS), turbidity, organic content, pH and the concentration of scale forming salts and non-ionic fouling species.
- Relate desalination costs to the quality and variability of the source water. This variability can have an impact on the pre-treatment required (the impact is, to some extent, dependent on the type of desalination plant selected) and therefore it will be necessary to comment in some detail on the quality of the source water and in particular to quality variations. It is essential that the requirements and costs associated with pre-treatment and waste disposal or release be fully assessed.
- Investigate the need for pre-treatment where required, with particular reference to biological fouling and the need to limit maintenance costs.
- Investigate the method of disposal or reuse of saline effluent providing full details of the method and costs associated with ensuring and maintaining the sustainability of the methods of disposal or reuse to be adopted.
- Undertake an environmental assessment identifying any adverse impacts and the works or controls required to minimise these impacts.
- Undertake a social impact assessment identifying any adverse impacts and the works or measures required to minimise these impacts.
- Investigate the maintenance requirements including plant and component life. Report on the technical expertise required to operate and manage the various processes considered.
- Confirm the capacity requirements of a pipeline to CQU distribution system in addition to Rockhampton City Council's pipeline system. Consideration should include the benefits of utilising a desalination plant to provide a based flow with the existing system meeting demand fluctuations.
- Identify pipeline sizing and route selection options including pump station and desalination plant location.
- Provide a plan of the complete installation required showing all components.
- Prepare capital and operating cost estimates.

3 Summary

An overview of solar thermal desalination technologies is presented. Solar desalination processes can be devised in two categories: direct and indirect collection systems. The "direct method" uses solar energy to produce distillate directly in the solar collector, whereas indirect solar desalination combines conventional desalination techniques such as multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and Electrodialysis with solar collectors for heat generation. Solar thermal desalination plants utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification/dehumidification, multi-stage flash (MSF), multi-effect distillation (MED) and membrane distillation (MD). Authors are currently undertaking a project on developing a solar desalination process for waste/drainage water at Central Queensland University, Australia.

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