ENERGY AND EXERGY PERFORMANCE ANALYSIS OF AN EVACUATED MULTI-STAGE SOLAR WATER DESALINATION SYSTEM

H. Sharon, P. Venkata Sai, K.S. Reddy
Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai – 600 036, INDIA

Keywords: Desalination, Potable Water, Latent Heat Utilization, Multi-Stage Evacuated Unit, Solar Energy, Thermodynamic Analyses, Enviro-Economic Analysis

Contents

Summary

Potable water is an essential requirement for the survival of humanity and other forms of life on our planet. It is indispensable in industry, agriculture, animal husbandry and other socioeconomic activities. The total stock of water on our planet is constant and the fresh water part in it is too small to meet the needs of these sectors. Fresh water production from saline water is an effective solution. Several desalination technologies have been developed and applied over the years. However, certain disadvantages of the existing processes such as high energy consumption, negative impacts on aquatic life, and emissions affecting the environment have been realized. It was also found that transportation of desalinated water from the large scale centralized desalination units based on these technologies to remote and rural locations is also expensive. Considering the abundance of solar energy in rural, remote, coastal, arid and semi-arid zones of the globe, decentralized renewable energy powered desalting units are highly preferable to bring down these costs. Low distillate production and low efficiency of simple solar stills motivated the development of active multi-effect/stage solar desalination units, which have the capability to meet small to medium scale potable water requirements at reduced costs.

In this chapter, various concepts, types and methods of solar energy driven desalination processes to improve productivity of solar desalting units are introduced. The focus of this work is to present the principles, thermodynamic analysis, heat and mass transfer phenomena and discuss the influence of certain parameters on the performance of some multi-stage solar desalination processes in detail. An assessment of performance in terms of technology and economics of multi-stage solar desalination units is made here relative to other units to justify their superiority and/or viability.

1. Introduction

Water is one of the most abundant and precious resources covering three fourth of the earth’s surface. Nearly, 97.0% of it is salt water and the remaining 3.0% only is fresh water which is distributed across the globe in rivers, lakes, ground water, glaciers and ice caps (at poles). Around 70.0% of this 3.0% fresh water is in the form of glaciers, permanent snow cover, ice and permafrost. Although ground water has a share of 30.0% of the total fresh water, most of this is hard to get. Rivers and lakes contain only 0.25% of the total fresh water reserve (Al-Ghamdi et al, 2014). Due to increase in population, urbanization, inadequate rainfall and increased ground water salinity, depletion of fresh water reserves is increasing rapidly in recent decades. In developing countries, 90.0% of wastewater is directly released into rivers and other water streams polluting freshwater bodies (Eltawil et al, 2009). Many regions on earth are facing shortage of potable water especially in the northern parts of Africa, Middle East and many parts of highly populated India (Shatat et al, 2013). These regions struggle to balance the depleting fresh water resources with the increasing demands of rising population. It is expected that global population will rise to 10.0 billion by 2050 from the present value of 7.7 billion (Berenguel-Felices et al, 2020). United Nations Organization has estimated that nearly 1800 million people around the world will be under severe water scarcity by 2025.This has led to search for other alternative sources of fresh water of which treatment of abundant sea water reserves appears as a viable option. Hence, desalination of sea water is a major option for fresh water production in coastal regions to tackle fresh water scarcity.

Desalination is widely adopted in regions of Middle East, Africa, Asia, Europe, North America, South America, Central America and Australia (Sharon and Reddy, 2015a). The most common desalination technologies are multi-stage distillation, multi-effect distillation, reverse osmosis, vapour compression and electro-dialysis. These desalination technologies require huge amounts of energy for operation and are conventionally powered by fossil fuels. It has been estimated that to produce 13.0 million m^3 of potable water per day there is a requirement of 130.0 million tons of oil per year (Eltawil et al, 2009). The developing and under-developed nations cannot not afford budgets for such energy requirements due to lack of fossil fuel resources or due to their economic situation in which they often import fossil fuels for their other activities. With fossil fuels burnt for desalination, environmental pollution is a growing concern due to the threat of global warming and greenhouse gas emissions which affect life on this planet very significantly. Generally, the world's arid regions have a great potential for renewable energy and at present nearly 60.0% of major cities around the globe are located in coastal zones with about 40.0% of global population living within 100.0 kilometres of the coast due to various economic benefits (Baztan et al, 2015). Therefore, renewable energy powered desalination technologies is a potential option to compensate for the fresh water deficiency in these regions. Renewable sources of energy - solar, wind and geothermal are common. Among these, solar energy holds nearly 57.0% of renewable energy powered desalination market (Sharon and Reddy, 2015a). With the extensive research carried out in solar powered desalination technologies, these processes are evolving into energy efficient and highly economic option for tackling water scarcity. Solar based desalination technologies also mitigate greenhouse gas emissions which is a serious issue with fossil fuel based processes.

2. Solar Thermal Desalination – Fundamentals and Concepts

Desalination refers to the removal of salts from saline/sea water. In a desalination process, fresh water is the main product and salt/concentrate is the by-product. Seawater is abundant and is mostly used as feed in desalination plants for producing potable water. Separating salt from sea water is an energy intensive process and the energy needed depends on the type of desalination process; feed water salt concentration, final water quality required and capacity of desalination plant. Energy required for producing 1.0 m^3 of desalinated water from surface water, groundwater and seawater are 0.37, 0.48 and 2.58-8.50 kWh, respectively. Energy requirements and impacts of conventional desalination units are tabulated in Table. 1. This scenario indicates high energy requirement along with direct and indirect negative environment impacts associated with desalination industries. Nearly half of the operating costs of desalination units are spent for meeting their electrical and thermal energy demands. Greenhouse gas emission from desalination plants alone will be around 0.4 billion tons of CO_2 equivalent by 2050. The negative impacts associated with conventional large scale desalination units are shown in Figure 1. Hence, usage of sustainable energy sources for powering/operating these units is the only option available to minimize these negative impacts (Nassrullah et al, 2020).

Desalination processes in general can be broadly classified into thermal and membrane categories. In thermal processes, sea water is heated to the required temperature and allowed to evaporate under ambient or reduced pressure to produce vapors in distillation chambers. These vapors are then condensed and used for human consumption and process industries. In a membrane process, potable water is generated from sea water by allowing water molecules from high concentration side to pass through a semi-permeable membrane. In the case of reverse osmosis (RO) process this is done by applying pressure higher than the osmotic pressure. In the case of electro dialysis it is by applying required electrical potential (Sharon and Reddy 2015a) allowing passage of ions through membranes.

In the case of solar thermal desalination processes, solar energy is used to heat feed sea water to generate water vapor. The concept of solar thermal desalination can be well understood through the global hydrological cycle. A schematic of this cycle is shown in Figure 2**.** Heat energy from the sun evaporates water from the surface of the earth. These generated water vapors rise up as clouds and then condense as rain. This precipitation returns water back to the land, oceans etc. (Enhancedlearning, 2020). A solar thermal desalination unit consists of an evaporator and a condenser. The evaporator traps solar energy and heats up feed water creating vapors which rise up and move towards the condenser due to partial pressure difference maintained in between. These water vapors condense into potable water which is collected. The schematic of a solar thermal desalination unit is shown in Figure 3 to illustrate its working principle**.**

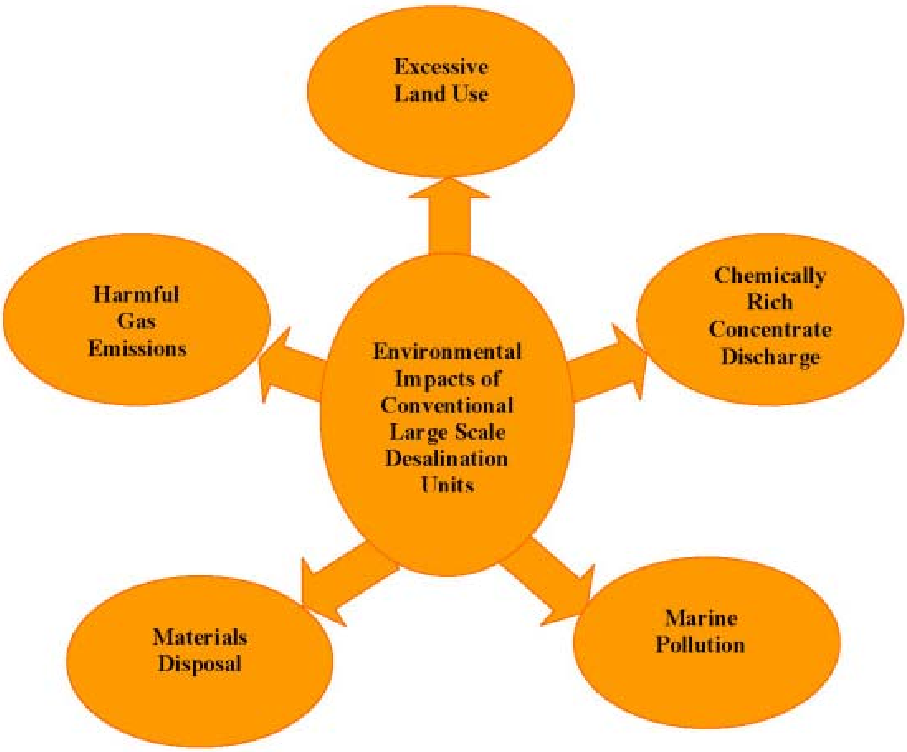

Figure 1. Negative impacts of conventional large scale desalination units

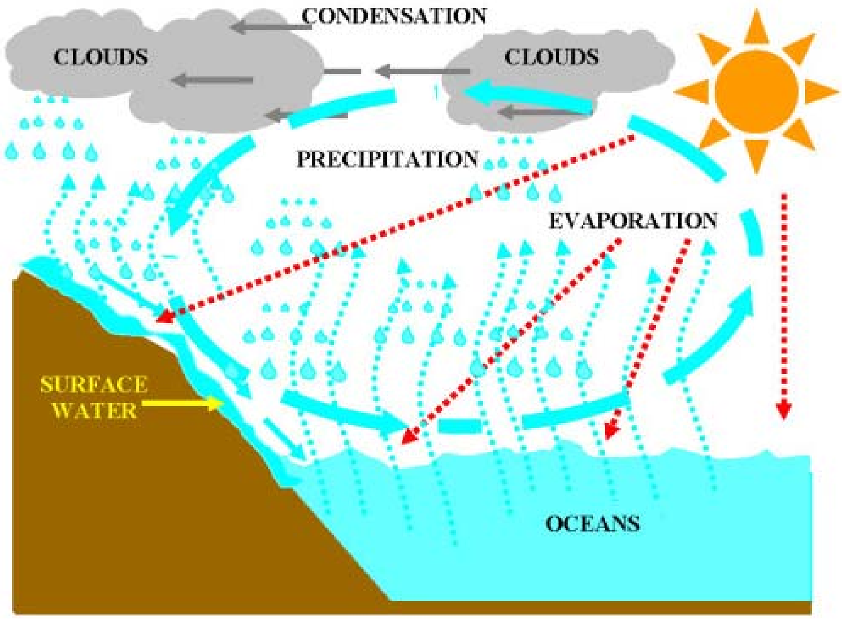

Figure 2. A schematic of the global hydrological cycle

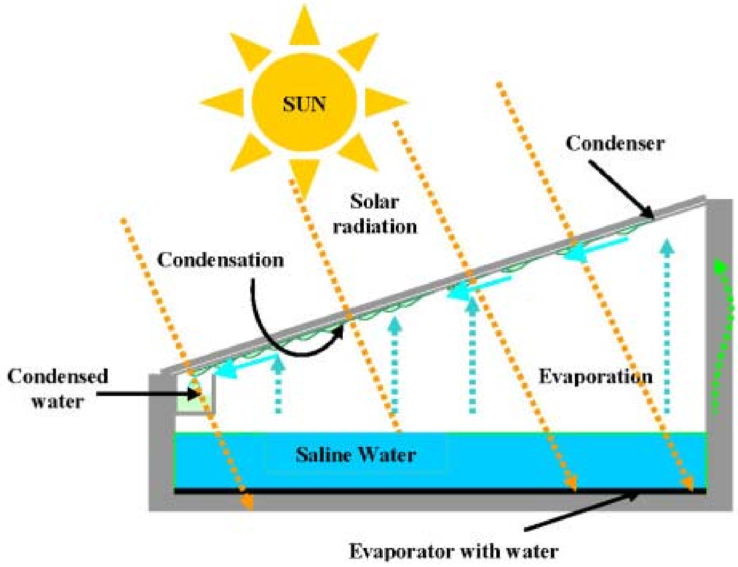

Figure 3. A schematic of solar thermal desalination working principle

Technology		**MSF**	**MED**	**MVC**	**RO**	**ED**
Thermal Energy	(kJ/kg)	250-300	150-220	-	-	-
Electrical Energy	(kWh/m^3 of distillate)	3.5-5.0	1.5-2.5	11.0-12.0	5.0-9.0	2.6-5.5
Harmful gas emissions	(kg of CO_2/m^3 of distillate)	13.5-22.5	7.2-18.1	9.9-10.8	4.5-8.1	2.3-5.0
Distillate quality	(ppm)	< 10	< 10	< 10	400-500	150-500

Table 1. Conventional Desalination Technologies – Energy Requirements and Harmful Gas Emissions (Gude et al. 2010 and Al-Karaghouli and Kazmerski 2013)

3. Solar Thermal Desalination Processes for Potable Water Production

Thermal desalination in general is more advantageous than membrane desalination as it does not require feed water pre-treatment and can produce high quality distillate from any low quality water. One of the major drawbacks of thermal desalination process is its huge energy consumption. At least, 27.4 kg of oil is consumed to produce 1.0 m^3 of distillate in thermal process which also leads to huge CO_2 emission. In the water scarce zones in the world which are blessed with abundant solar radiation which can be effectively utilized to meet the energy demands of desalination plants. Solar thermal desalination processes can be classified according to two types of heating- direct and indirect. Solar radiation directly heats up feed water in a distillation chamber to produce vapors in the direct heating type desalination units. In the case of indirect type systems, feed water is heated with the aid of solar collectors in distillation chambers or heated externally and fed to distillation chamber for evaporation. All high capacity commercial desalination units like multi-stage flash, multi-effect distillation and vapor compression units are of indirect type. A solar basin still shown in Figure 3 comes under the direct type and its productivity is low, i.e., in the range of 2.0 to 3.0 $L/d.m^2$. Productivity of this direct type unit can be further enhanced by using energy storage, reflecting mirrors, external condensers, cooling glass cover with flowing water and reusing latent heat of vaporization.

The advantages and drawbacks of the direct type solar desalination units are:

Advantages:

a. Easy to construct, operate and maintain
b. Low initial investment
c. Low environmental impact
d. Brine can be concentrated to achieve zero liquid discharge

Disadvantages:

a. Large area requirement for given production capacity
b. Low performance and productivity
c. High water production cost
d. Not suitable if water demand exceeds 0.2 m^3/d

The advantages and drawbacks of indirect type solar desalination units are:

Advantages:

a. Low area requirement for given production capacity
b. Highly efficient and more suitable for large scale water production
c. Low water production cost

Disadvantages:

a. Require heavy equipments and high capital cost
b. Require electrical power in addition to thermal energy
c. Corrosion is a major problem
d. High environmental impacts due to feed water intake and hot brine discharge

4. Multi-Stage Solar Desalination Systems

4.1. Concept of Multi-Stage Solar Desalination Systems

In multi-stage desalination systems, latent heat of condensation from one stage of the distillation unit is supplied for next consecutive stage. Hence, the combined benefit of reduced energy requirement and increased yield is possible with these units.

4.2. Classification and System Description

Multi-stage desalinations systems are generally classified according to the following features as shown in Figure 4.

a. **Feed water heating mode (Active or passive)**: Feed water is heated within the distillation unit by solar radiation in passive units. In the case of active units, feed water is heated in external units by heat from solar collectors or waste heat from other processes and fed into the distillation unit for evaporation.

b. **System orientation (Horizontal or vertical)**: Evaporation stages are parallel or nearly parallel to the ground in the case of horizontal units. Evaporation stages are vertical to the ground in the case of vertical units. Horizontal units have stagnant water mass or free flowing water. Vertical units are sub classified into convection type and diffusion type. In the convection type, the gap between evaporating and condensing surfaces is higher to facilitate movement of air and transfer of water vapor from the evaporating section to condenser surfaces (Kiatsiriroat et al, 1987; Reddy and Sharon, 2016). Gaps maintained in convection units are about 50.00 mm (Zhang et al, 2020). In the case of diffusion type, the gap is less than 10.00 mm, due to which convection is suppressed and water vapors reach condensing surfaces only by diffusion (Tanaka et al, 2000; Tanaka and Nakatake, 2004).

c. **Feed water distribution (Series or Parallel)**: Feed water is divided and distributed to all stages in parallel flow mode. These units have a number of inlets and outlets (Reddy et al, 2012). In the case of series flow, feed water enters through one inlet of the uppermost stage and flows over other stages by gravity and exits the unit through the outlet of the bottom most stage (Reddy and Sharon, 2017).

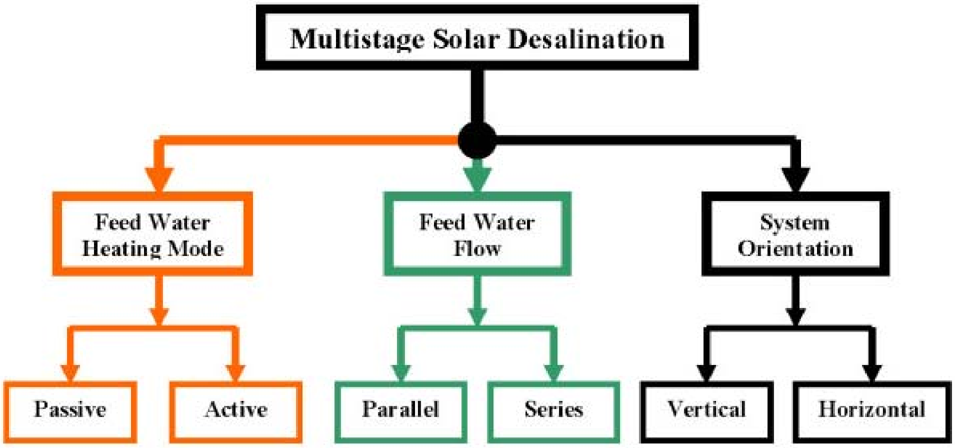

Figure 4. Classification of multistage solar desalination systems

In the multistage desalination unit with parallel flow of feed water analyzed by Reddy et al (2012) multiple rectangular trays are arranged one over another with a fixed gap between them as shown in Figure 5. The top surface of each tray acts as an evaporating surface and the bottom surface of each tray acts as a condensing surface. These trays are arranged with a tilt angle with respect to the horizontal for natural motion of condensed droplets. A pair of consecutive trays constitutes a stage. A number of these stages stacked upon one another makes a multi-stage desalination unit. Over the top most stage, a reservoir is created as the feed water source. Feed water from reservoir is heated using solar flat plate collectors or by any other auxiliary source and fed into all the stages at controlled mass flow rate. A porous silk cloth is provided over the top surface of each tray for uniform spread of feed water over the evaporating surface. This ensures high evaporation owing to the thin water film thickness. The vapors formed by evaporation move towards the condensing surface and get condensed due to temperature difference with it forming droplets. These droplets slide downwards and are collected in a distillate collection trough. The left-over brine from each stage is collected separately in a brine collection tank.

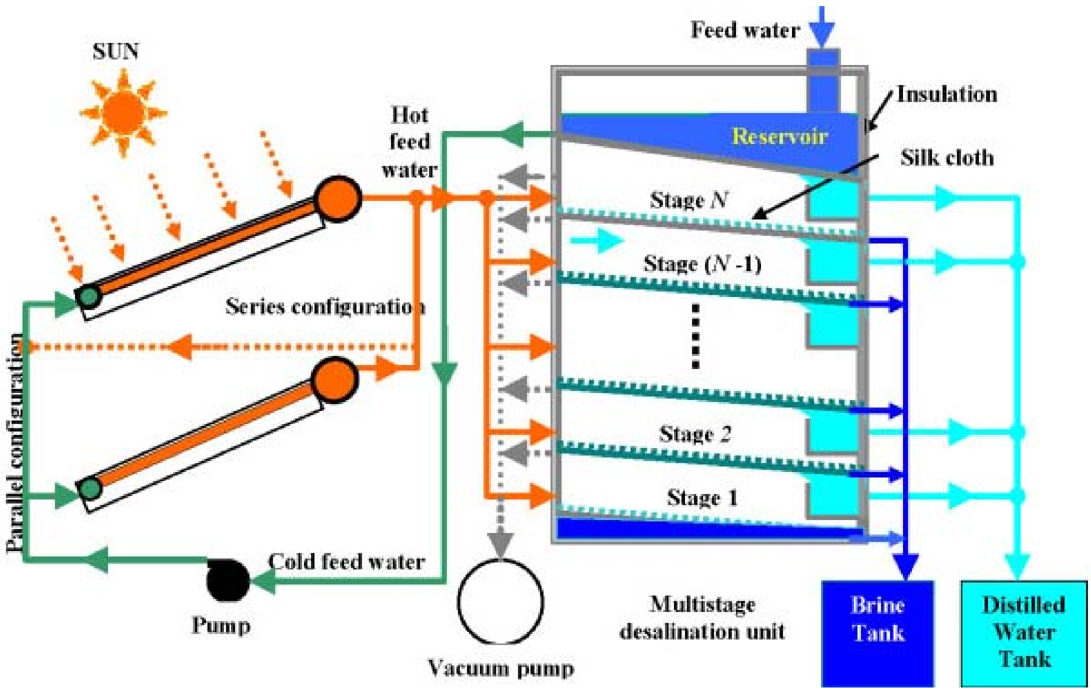

Figure 5. Multi-stage desalination unit with feed water flow coupled with solar flat plate collectors.

In a multi-stage desalination unit with stagnant feed water level analyzed by Shatat and Mahkamov (2010), sheets are welded into rectangular form steel casing creating stages as shown in Figure 6. The bottom most stage has flat bottom which is denoted as Stage 1 whereas all other stages are formed with ‘V’ shaped bottoms and are denoted as Stages 2 to *N*. A reservoir for feed water is designed over the Stage *N*. Overflow pipes are used to feed saline water from the reservoir to Stage *N* and from there into the next consecutive stages. A pump circulates a low temperature heat transfer fluid into the solar collector field. The temperature of heat transfer fluid is increased in solar flat plate collectors. This high temperature heat transfer fluid exchanges heat to Stage 1 of the multi-stage unit using a horizontal serpentine tubular heat exchanger. The process of evaporation is same as the previous case and the vapors formed are condensed over the condensing surfaces. A simple long triangular collection trough is placed at the centre of the stages to collect the distillate.

In multi-stage desalination unit with stagnant feed water arrangement analyzed by Fernández and Chargoy (1990), the organization of stages is in the same manner as in the system studied by Shatat and Mahkamov (2010) but with different tray bottom shape. Though the bottom most stage has flat surface, other stages have trays of inverted V-shaped or W shaped bottom as shown in Figure 6. In this system, feeding in each stage is done manually. The heat energy is supplied only to the bottom stage with flat surface using a heat exchanger. The condensed distillate is collected in the two long collector ducts located underneath the bottom edge of sloped trays. These ducts also prevent the leakage of vapor into next stage through gaps in tray seats.

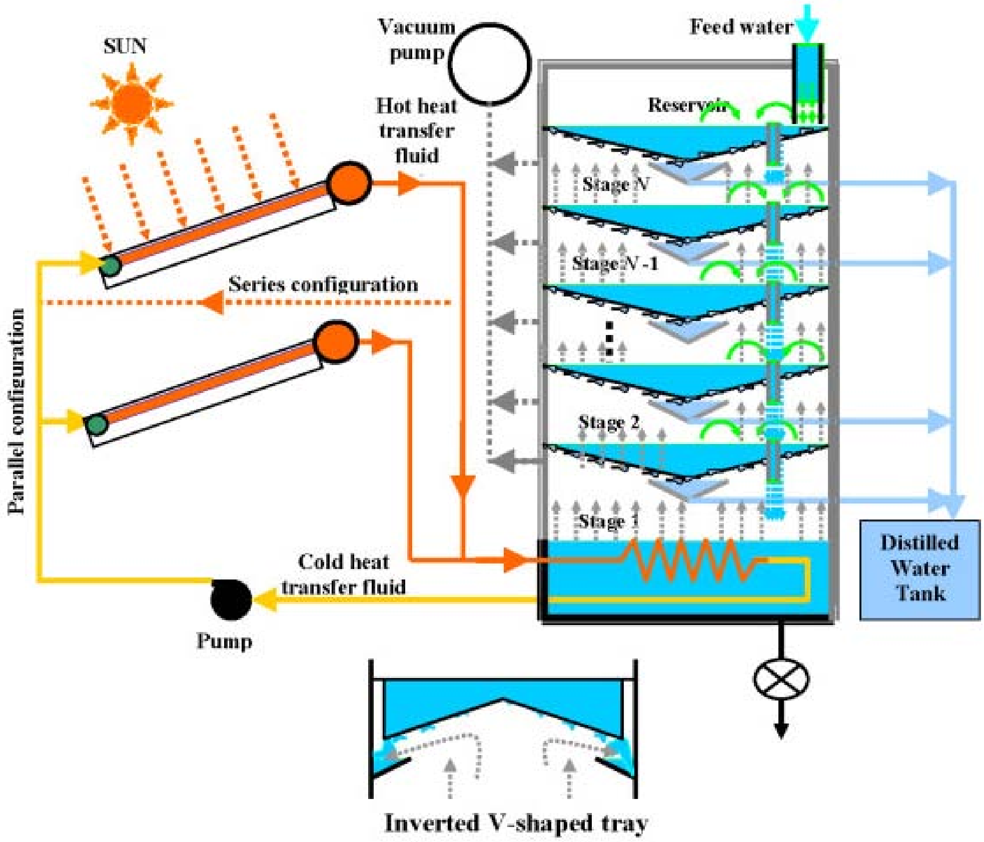

Figure 6. Multi-stage desalination unit with stagnant feed water level coupled with solar flat plate collectors and an alternate inverted V-shaped tray.

In the active multistage series flow solar distillation unit proposed and analyzed by Reddy and Sharon (2017), a bottom basin and a number of tilted metallic partition trays are enclosed in a vertical rectangular chamber as shown in Figure 7. The arrangement of these metallic partition trays one over the other is like in a stair case (between the landings) in a multi storey building. For the free flow of feed water under gravity and free motion of condensed vapors, these metallic partition trays are tilted at an angle with the horizontal plane. The evaporating surfaces of metallic trays are lined with capillary cloth for proper spread of feed water for evaporation. At the bottom end of each of the condensing surfaces of metallic trays, a distillate collection trough is attached to collect distilled water. The feed water is stored in a feed water reservoir from which it is supplied to the stages of distillation unit. Initially, the bottom basin is filled with feed water by opening Valve V1 and overflow Valve V2 whereas all the other valves are closed. Once the desired water level is achieved in bottom basin, water overflows through Valve V2 and the Valves V1 and V2 are now closed. The feed water in the bottom basin is sent to the solar flat plate collector for using Valves V3, V4 and V5 to raise its temperature. At the same time, the feed water in the reservoir is allowed to flow into stages by opening stage Valve SV. The bottom and side surfaces of the distillation unit are insulated to minimize the heat losses to the atmosphere. Upon heat exchange from solar flat plate collectors, the heated feed water is supplied to the bottom basin of the distillation unit where evaporation occurs. The water vapors thus formed rise up and condense over the condensing surface which is at a relatively lower temperature relative to the bottom basin. The latent heat of condensation released will be utilized to enhance the evaporation of feed water flowing over that surface. This evaporation-condensation process continues in later stages with effective utilization of latent heat of condensation across whole the unit. As the feed water flowing from the reservoir through the various stages loses certain amount of its mass by evaporation, the remaining concentrated brine is collected in the brine tank from the evaporative surface of Stage 2. The condensate from each stage is collected in the distillate collection trough and led into the distillate tank. The other side of the condensing the surface of the last stage is exposed to the atmosphere to which it loses the obtained heat energy by convection and radiation. To reduce the temperature of the condensing surface further, the other side of the condensing surface is lined with wetted wick due to which evaporative cooling takes place. The distillation unit is also operated under reduced pressure with the help of a vacuum pump.

In a vertical multi-effect solar desalination unit (Figure 8) analyzed by Reddy and Sharon (2016), a number of vertical chambers or stages are created with trays and partitions. The inner side of each chamber acts as an evaporating surface whereas the outer side of the adjacent one acts a condensing surface as shown in Figure 8. At the end of the last stage, a feed water reservoir is provided which acts as a condenser for the last stage. In each stage, feed water is supplied through individual feed water troughs from the top maintaining thin film flow over the evaporator surfaces. The distillate condensed over the condensing surface is collected in a distillate trough. This unit is said to be active due to the integration of the unit with solar flat plate collector for external feed water heating. The movement of vapors towards the condensing surface takes place due to the difference in partial pressures and the latent heat of condensation is transferred to from one stage to the next. The rate of evaporation tends to increase from the initial to the final stage due to effective utilization of latent heat from the preceding effects. This unit is provided with a vacuum pump for low pressure operation for enhanced evaporation to obtain higher distillate yield.

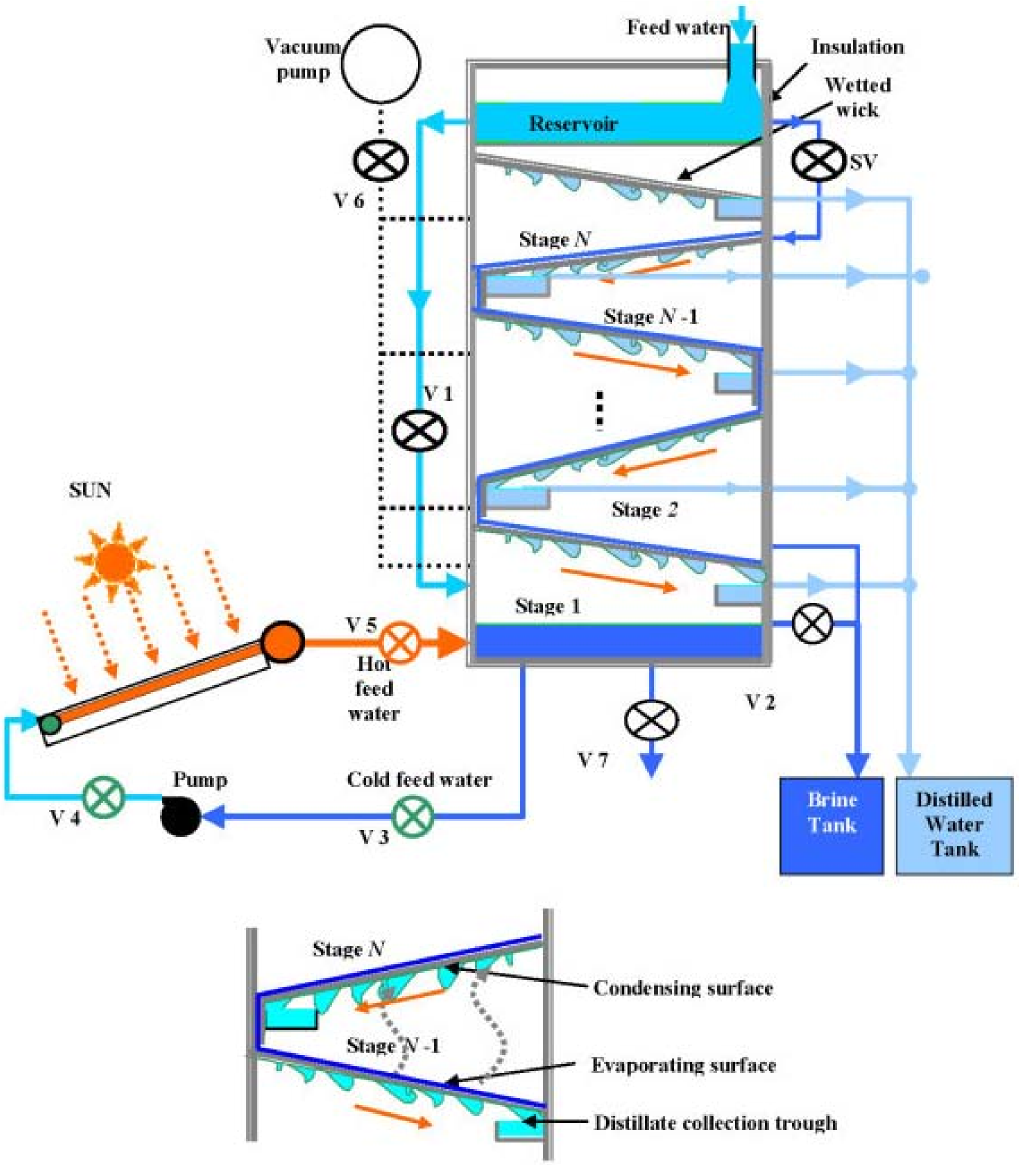

Figure 7. Active multistage series flow solar distillation unit analyzed by (Reddy and Sharon, 2017).

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Biographical Sketches

Dr. K. Srinivas Reddy is a Professor of Mechanical Engineering at Indian Institute of Technology Madras and he is also an honorary professor at University of Exeter, UK. He is a Fellow of the National Academy of Engineering (FNAE) and he is specialist in renewable energy with special research interests on concentrating solar power, energy efficiency and environment. He has 8 patent applications and more than 280 publications of which, 150 papers in reputed international journals, including five review articles on solar energy systems and energy storage. His co-authored book on "Sustainable energy and the environment: a clean technology approach" Published by Springer and book chapters on solar energy systems are popular among energy and environment community. Prof. Reddy is actively involved in the implementation of solar thermal technologies for power generation and process heat applications. He has executed several research projects related to solar energy and energy and environment funded by various national and international agencies.

H. Sharon received the BE degree (Mechanical) from Government College of Engineering Tirunelveli in 2009, the ME degree (Energy) from Anna University of Technology Tirunelveli in 2011 and the Ph.D. degree (Mechanical-Thermal Sciences) form the Indian Institute of Technology Madras in 2018. He has published 22 peer reviewed journal articles, 13 conference papers, 2 book chapters and 1 patent. He was awarded Institute Research Award and Shri. J. C. Bose Patent Award in 2017 by Indian Institute of Technology Madras for his research works. His research interests are adoption of Solar Energy for Desalination, Wastewater Treatment and Power Generation and conversion of Waste to Energy. He served as Lecturer in National Engineering College Kovilpatti from 2011 to 2012 after his Masters. He also worked as Assistant Professor in Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu, India from 2019 to 2020 after his PhD. At present he is working as Adhoc faculty in National Institute of Technology Andhra Pradesh.

Policherla Venkata Sai received his B.Tech degree in Mechanical Engineering from SASTRA University, Thanjavur, India in 2016. Presently, he is pursuing his Doctorate at Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras. His research work is mainly focused on application of solar thermal energy for water treatment and food processing using novel approaches.