International Journal of Trend in Scientific Research and Development (IJTSRD)
International Conference of Multidisciplinary Research – September 2023
Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

A Review of the Performance Analysis of the Different Designs of Solar Stills on Solar Desalination

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Abstract: A solar still distills water with substances dissolved in it by using the heat of the Sun to evaporate water so that it may be cooled and collected, thereby purifying it. They are used in areas where drinking water is unavailable, so that clean water is obtained from dirty water or from plants by exposing them to sunlight.

Still types include large scale concentrated solar stills and condensation traps. In a solar still, impure water is contained outside the collector, where it is evaporated by sunlight shining through a transparent collector. The pure water vapour condenses on the cool inside surface and drips into a tank.

Distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, its vapour rises, condensing into water again as it cools. This process leaves behind impurities, such as salts and heavy metals, and eliminates microbiological organisms. The end result is pure (potable) water.

KEYWORDS: *solar, stills, desalination, designs, performance, analysis.*

INTRODUCTION

Pit still

A collector is placed at the bottom of a pit. Branches are placed vertically in the pit. The branches are long enough to extend over the edge of the pit and form a funnel to direct the water into the collector. A lid is then built over this funnel, using more branches, leaves, grasses, etc. Water is collected each morning.

This method relies on the formation of dew or frost on the receptacle, funnel, and lid. Forming dew collects on and runs down the outside of the funnel and into the receptacle. This water would typically evaporate with the morning sun and thus vanish, but the lid traps the evaporating water and raises the humidity within the trap, reducing the amount of lost water. The shade produced by the lid also reduces the temperature within the trap, which further reduces the rate of water loss to evaporation.

A solar still can be constructed with two–four stones, plastic film or transparent glass, a central weight to make the funnel and a container for the condensate.[3] Better materials improve efficiency. A single sheet of plastic can replace the branches and leaves. Greater efficiency arises because the plastic is waterproof, preventing water vapour from escaping. The sheet is attached to the ground on all sides with stones or earth. Weighting the centre of the sheet forms the funnel. Condensate runs down it into the receptacle. One study of pit distillation found that angling the lid at 30 degrees angle captured the most water. The optimal water depth was about 25 millimetres (1 in).[4]

Transpiration

During photosynthesis plants release water through transpiration. Water can be obtained by enclosing a leafy tree branch in clear plastic,[5] capturing water vapour released by the tree.[6] The plastic allows photosynthesis to continue.

In a 2009 study, variations to the angle of plastic and increasing the internal temperature versus the outside temperature improved output volumes.

Unless relieved the vapour pressure around the branch can rise so high that the leaves can no longer transpire, requiring the water to be removed frequently.

Alternatively, clumps of grass or small bushes can be placed inside the bag. The foliage must be replaced at regular intervals, particularly if the foliage is uprooted.

Efficiency is greatest when the bag receives maximum sunshine. Soft, pulpy roots yield the greatest amount of liquid for the least amount of effort.

Wick

The wick type solar still is a vapour-tight glass-topped box with an angled roof.[7] Water is poured in from the top. It is heated by sunlight and evaporates. It condenses on the underside of the glass and runs into the connecting pipe at the bottom. Wicks separate the water into banks to increase surface area. The more wicks, the more heat reaches the water.

To aid in absorbing more heat, wicks can be blackened. Glass absorbs less heat than plastic at higher temperatures, although glass is not as flexible.

A plastic net can catch the water before it falls into the container and give it more time to heat.

Additives

When distilling brine or other polluted water, adding a dye can increase the amount of solar radiation absorbed.

Reverse still

A reverse still uses the temperature difference between solar-heated ambient air and the device to condense ambient water vapour. One such device produces water without external power. It features an inverted cone on top to deflect ambient heat in the air, and to keep sunlight off the upper surface of the box. This surface is a sheet of glass coated with multiple layers of a polymer and silver.[8]

It reflects sunlight to reduce surface heating. Residual heat that is not reflected is reemitted in a specific (infrared) wavelength so that it passes through the atmosphere into space. The box can be as much as 15 °C (27 °F) cooler than the ambient temperature. That stimulates condensation, which gathers on the ceiling. This ceiling is coated in a superhydrophobic material, so that the condensate forms into droplets and falls into a collector. A test system yielded 4.6 ml (0.16 US fl oz) of water per day, using a 10 cm (3.9 in) surface or approximately 1.3 L/m^2 (0.28 gal/ft^2) per day.[8]

Efficiency

Condensation traps are sources for extending or supplementing existing water sources or supplies. A trap measuring 40 cm (16 in) in diameter by 30 cm (12 in) deep yields around 100 to 150 mL (3.4 to 5.1 US fl oz) per day.

Urinating into the pit before adding the receptacle allows some of the urine's water content to be recovered.

A pit still may be too inefficient as a survival still, because of the energy/water required for construction.[9] In desert environments water needs can exceed 3.8 litres (1 US gal) per day for a person at rest, while still production may average only 240 millilitres (8 US fl oz).[9][10] Several days of water collection may be required to equal the water lost during construction.[10]

Applications

Remote sites

Solar stills are used in cases where rain, piped, or well water is impractical, such as in remote homes or during power outages.[11] In subtropical hurricane target areas that can lose power for days, solar distillation can provide an alternative source of clean water.

Solar-powered desalination systems can be installed in remote locations where there is little or no infrastructure or energy grid. Solar is still affordable, eco-friendly, and considered an effective method amongst other conventional distillation techniques. Solar still is very effective, especially for supplying fresh water for islanders. This makes them ideal for use in rural areas or developing countries where access to clean water is limited. [12] [13]

Survival

Solar stills have been used by ocean-stranded pilots and included in life raft emergency kits.[1]

Using a condensation trap to distill urine will remove the urea and salt, recycling the body's water.[14]

Wastewater treatment

Solar stills have also been used for the treatment of municipal wastewater,[15] the dewatering of sewage sludge [16] as well as for olive mill wastewater management.[17]

DISCUSSION

Solar desalination is a desalination technique powered by solar energy. The two common methods are direct (thermal) and indirect (photovoltaic).[1]

History

Solar distillation has been used for thousands of years. Early Greek mariners and Persian alchemists produced both freshwater and medicinal distillates. Solar stills were the first method used on a large scale to convert contaminated water into a potable form.[2]

In 1870 the first US patent was granted for a solar distillation device to Norman Wheeler and Walton Evans.[3] Two years later in Las Salinas, Chile, Swedish engineer Charles Wilson began building a solar distillation plant to supply freshwater to workers at a saltpeter and silver mine. It operated continuously for 40 years and distilled an average of 22.7 m^3 of water a day using the effluent from mining operations as its feed water.[4]

Solar desalination in the United States began in the early 1950s when Congress passed the Conversion of Saline Water Act, which led to the establishment of the Office of Saline Water (OSW) in 1955. OSW's main function was to administer funds for desalination research and development projects.[5] One of five demonstration plants was located in Daytona Beach, Florida. Many of the projects were aimed at solving water scarcity issues in remote desert and coastal communities.[4] In the 1960s and 1970s several distillation plants were constructed on the Greek isles with capacities ranging from 2000 to 8500 m^3/day.[2] In 1984 a plant was constructed in Abu-Dhabi with a capacity of 120 m^3/day that is still in operation.[4] In Italy, an open source design called "the Eliodomestico" by Gabriele Diamanti was developed for personal costing $50.[6]

Of the estimated 22 million m^3 daily freshwater produced through desalination worldwide, less than 1% uses solar energy.[2] The prevailing methods of desalination, MSF and RO, are energy-intensive and rely heavily on fossil fuels.[7] Because of inexpensive methods of freshwater delivery and abundant low-cost energy resources, solar distillation has been viewed as cost-prohibitive and impractical.[2] It is estimated that desalination plants powered by conventional fuels consume the equivalent of 203 million tons of fuel a year.[2]

In the direct (distillation) method, a solar collector is coupled with a distilling mechanism.[9] Solar stills of this type are described in survival guides, provided in marine survival kits, and employed in many small desalination and distillation plants. Water production is proportional to the area of the solar surface and solar incidence angle and has an average estimated value of 3–4 litres per square metre (0.074–0.098 US gal/sq ft).[2] Because of this proportionality and the relatively high cost of property and material for construction, distillation tends to favor plants with production capacities less than 200 m^3/d (53,000 US gal/d).[2]

Indirect desalination employs a solar collection array, consisting of photovoltaic and/or fluid-based thermal collectors, and a separate conventional desalination plant.[9] Many arrangements have been analyzed, experimentally tested and deployed. Categories include multiple-effect humidification (MEH), multi-stage flash distillation (MSF), multiple-effect distillation (MED), multiple-effect boiling (MEB), humidification–dehumidification (HDH), reverse osmosis (RO), and freeze-effect distillation.[7]

Indirect solar desalination systems using photovoltaic (PV) panels and reverse osmosis (RO) have been in use since 2009. Output by 2013 reached 1,600 litres (420 US gal) per hour per system, and 200 litres (53 US gal) per day per square metre of PV panel.[10][11] Utirik Atoll in the Pacific Ocean has been supplied with fresh water this way since 2010.[12]

Indirect solar desalination by a form of humidification/dehumidification is in use in the seawater greenhouse.

Indirect

Large solar desalination plants typically use indirect methods.[13] Indirect solar desalination processes are categorized into single-phase processes (membrane based) and phase change processes (non-membrane based).[14] Single-phase desalination use photovoltaics to produce electricity that drive pumps.[15] Phase-change (or multi-phase) solar desalination is not membrane-based.[16]

Single-phase desalination processes include reverse osmosis and membrane distillation, where membranes filter water from contaminants.[14][16] As of 2014 reverse osmosis (RO) made up about 52% of indirect methods.[13][17][18] Pumps push salt water through RO modules at high pressure.[14][17] RO systems depend on pressure differences. A pressure of 55–65 bar is required to purify seawater. An average of 5 kWh/m^3 of energy is typically required to run a large-scale RO plant.[17] Membrane distillation (MD) utilizes pressure difference from two sides of a microporous hydrophobic membrane.[17][19] Fresh water can be extracted through four MD methods: Direct Contact (DCMD), Air Gap (AGMD), Sweeping Gas (SGMD) and Vacuum (VMD).[17][19] An estimated water cost of \$15/m^3 and \$18/m^3 support medium-scale solar-MD plants.[17][20] Energy consumption ranges from 200 to 300 kWh/m^3.[21]

Phase-change (or multi-phase) solar desalination[16][18][22] includes multi-stage flash, multi-effect distillation (MED), and thermal vapor compression (VC).[16] It is accomplished by using phase change materials (PCMs) to maximize latent heat storage and high temperatures.[23] MSF phase change temperatures range 80–120 °C, 40–100 °C for VC, and 50–90 °C for the MED method.[16][22] Multi-stage flash (MSF) requires seawater to travel through a series of vacuumed reactors held at successively lower pressures.[18] Heat is added to capture the latent heat of the vapor. As seawater flows through the reactors, steam is collected and is condensed to produce fresh water.[18] In Multi-effect distillation (MED), seawater flows through successively low pressure vessels and reuses latent heat to evaporate seawater for condensation.[18] MED desalination requires less energy than MSF due to higher efficiency in thermodynamic transfer rates.[18][22]

Direct

Direct methods use thermal energy to vaporize the seawater as part of a 2-phase separation. Such methods are relatively simple and require little space so they are normally used on small systems. However, they have a low production rate due to low operating temperature and pressure, so they are appropriate for systems that yield 200 m^3/day.[24]

Single-effect

This uses the same process as rainfall. A transparent cover encloses a pan where saline water is placed. The latter traps solar energy, evaporating the seawater. The vapor condenses on the inner face of a sloping transparent cover, leaving behind salts, inorganic and organic components and microbes.

The direct method achieves values of 4-5 L/m^2/day and efficiency of 30-40%.[25] Efficiency can be improved to 45% by using a double slope or an additional condenser.[26]

In a wick still, feed water flows slowly through a porous radiation-absorbing pad. This requires less water to be heated and is easier to change the angle towards the sun which saves time and achieves higher temperatures.

A diffusion still is composed of a hot storage tank coupled to a solar collector and the distillation unit. Heating is produced by the thermal diffusion between them.

Increasing the internal temperature using an external energy source can improve productivity.

Indirect multi-phase

Multi-stage flash distillation (MSF)

The multi-stage flash (MSF) method is a widely used technology for desalination, particularly in large-scale seawater desalination plants. It is based on the principle of utilizing the evaporation and condensation process to separate saltwater from freshwater.

In the MSF desalination process, seawater is heated and subjected to a series of flashings or rapid depressurizations in multiple stages. Each stage consists of a series of heat exchangers and flash chambers. The process typically involves the following steps:

1. Preheating: Seawater is initially preheated to reduce the energy required for subsequent stages. The preheated seawater then enters the first stage of the MSF system.
2. Flashing: In each stage, the preheated seawater is passed through a flash chamber, where its pressure is rapidly reduced. This sudden drop in pressure causes the water to flash into steam, leaving behind concentrated brine with high salt content.
3. Condensation: The steam produced in the flash chamber is then condensed on the surfaces of heat exchanger tubes. The condensation occurs as the steam comes into contact with colder seawater or with tubes carrying cool freshwater from previous stages.
4. Collection and extraction: The condensed freshwater is collected and collected as product water. It is then extracted from the system for storage and distribution, while the remaining brine is removed and disposed of properly.
5. Reheating and repetition: The brine from each stage is reheated, usually by steam extracted from the turbine that drives the process, and then introduced into the subsequent stage. This process is repeated in subsequent stages, with the number of stages determined by the desired level of freshwater production and the overall efficiency of the system.

The multi-stage flash (MSF) method, known for its high energy efficiency through the utilization of latent heat of vaporization during the flashing process, accounted for approximately 45% of the world's desalination capacity and a dominant 93% of thermal systems as recorded in 2009.[2]

In Margherita di Savoia, Italy a 50–60 m^3/day MSF plant uses a salinity gradient solar pond. In El Paso, Texas a similar project produces 19 m^3/day. In Kuwait a MSF facility uses parabolic trough collectors to provide solar thermal energy to produce 100 m^3 of fresh water a day.[7] And in Northern China an experimental, automatic, unmanned operation uses 80 m^2 of vacuum tube solar collectors coupled with a 1 kW wind turbine (to drive several small pumps) to produce 0.8 m^3/day.[27]

MSF solar distillation has an output capacity of 6–60 L/m^2/day versus the 3-4 L/m^2/day standard output of a solar still.[7] MSF experience poor efficiency during start-up or low energy periods. Achieving highest efficiency requires controlled pressure drops across each stage and steady energy input. As a result, solar applications require some form of thermal energy storage to deal with cloud interference, varying solar patterns, nocturnal operation, and seasonal temperature changes. As thermal energy storage capacity increases a more continuous process can be achieved and production rates approach maximum efficiency.[28]

Freezing
Although it has only been used on demonstration projects, this indirect method based on crystallization of the saline water has the advantage of the low energy required. Since the latent heat of fusion of water is 6,01 kJ/mole and the latent heat of vaporization at 100 °C is 40,66 kJ/mole, it should be cheaper in terms of energy cost. Furthermore, the corrosion risk is lower too. There is however a disadvantage related with the difficulties of mechanically moving mixtures of ice and liquid. The process has not been commercialized yet due to cost and difficulties with refrigeration systems.

The most studied way of using this process is the refrigeration freezing. A refrigeration cycle is used to cool the water stream to form ice, and after that those crystals are separated and melted to obtain fresh water. There are some recent examples of this solar powered processes: the unit constructed in Saudi Arabia by Chicago Bridge and Iron Inc. in the late 1980s, which was shut down for its inefficiency.

Nevertheless, there is a recent study for the saline groundwater [29] concluding that a plant capable of producing 1 million gal/day would produce water at a cost of $1.30/1000 gallons. Being this true, it would be a cost-competitive device with the reverse osmosis ones.

Problems with thermal systems
Inherent design problems face thermal solar desalination projects. First, the system's efficiency is governed by competing heat and mass transfer rates during evaporation and condensation.[1]

Second, the heat of condensation is valuable because it takes large amounts of solar energy to evaporate water and generate saturated, vapor-laden hot air. This energy is, by definition, transferred to the condenser's surface during condensation. With most solar stills, this heat is emitted as waste heat.

Solutions
Heat recovery allows the same heat input to be reused, providing several times the water.[1]

One solution is to reduce the pressure within the reservoir. This can be accomplished using a vacuum pump, and significantly decreases the required heat energy. For example, water at a pressure of 0.1 atmospheres boils at 50 °C (122 °F) rather than 100 °C (212 °F).[30]

Solar humidification–dehumidification
The solar humidification–dehumidification (HDH) process (also called the multiple-effect humidification–dehumidification process, solar multistage condensation evaporation cycle (SMCEC) or multiple-effect humidification (MEH)[31] mimics the natural water cycle on a shorter time frame by distilling water. Thermal energy produces water vapor that is condensed in a separate chamber. In sophisticated systems, waste heat is minimized by collecting the heat from the condensing water vapor and pre-heating the incoming water source.[32]

Single-phase solar desalination
In indirect, or single phase, solar-powered desalination, two systems are combined: a solar energy collection system (e.g. photovoltaic panels) and a desalination system such as reverse osmosis (RO). The main single-phase processes, generally membrane processes, consist of RO and electrodialysis (ED). Single phase desalination is predominantly accomplished with photovoltaics that produce electricity to drive RO pumps. Over 15,000 desalination plants operate around the world. Nearly 70% use RO, yielding 44% of desalination.[33] Alternative methods that use solar thermal collection to provide mechanical energy to drive RO are in development.

Reverse osmosis
RO is the most common desalination process due to its efficiency compared to thermal desalination systems, despite the need for water pre-treatment.[34] Economic and reliability considerations are the main challenges to improving PV powered RO desalination systems. However, plummeting PV panel costs make solar-powered desalination more feasible.

Solar-powered RO desalination is common in demonstration plants due to the modularity and scalability of both PV and RO systems. An economic analysis[35] that explored an optimisation strategy[36] of PV-powered RO reported favorable results.

PV converts solar radiation into direct-current (DC) electricity, which powers the RO unit. The intermittent nature of sunlight and its variable intensity throughout the day complicates PV efficiency prediction and limits night-time desalination. Batteries can store solar energy for later use. Similarly, thermal energy storage systems ensure constant performance after sunset and on cloudy days.[37]

Batteries allow continuous operation. Studies have indicated that intermittent operations can increase biofouling.[38]

Batteries remain expensive and require ongoing maintenance. Also, storing and retrieving energy from the battery lowers efficiency.[38]

Reported average cost of RO desalination is US$0.56/m^3. Using renewable energy, that cost could increase up to US$16/m^3.[33] Although renewable energy costs are greater, their use is increasing.

Electrodialysis
Both electrodialysis (ED) and reverse electrodialysis (RED) use selective ion transport through ion exchange membranes (IEMs) due either to the influence of concentration difference (RED) or electrical potential (ED).

In ED, an electrical force is applied to the electrodes; the cations travel toward the cathode and anions travel toward the anode. The exchange membranes only allow the passage of its permeable type (cation or anion), hence with this arrangement, diluted and concentrated salt solutions are placed in the space between the membranes (channels). The configuration of this stack can be either horizontal or vertical. The feed water passes in parallel through all the cells, providing a continuous flow of permeate and brine. Although this is a well-known process electrodialysis is not commercially suited for seawater desalination, because it can be used only for brackish water (TDS < 1000 ppm).[33] Due to the complexity for modeling ion transport phenomena in the channels, performance could be affected, considering the non-ideal behavior presented by the exchange membranes.[39]

The basic ED process could be modified and turned into RED, in which the polarity of the electrodes changes periodically, reversing the flow through the membranes. This limits the deposition of colloidal substances, which makes this a selfcleaning process, almost eliminating the need for chemical pre-treatment, making it economically attractive for brackish water.[40]

The use ED systems began in 1954, while RED was developed in the 1970s. These processes are used in over 1100 plants worldwide. The main advantages of PV in desalination plants is due to its suitability for small-scale plants. One example is in Japan, on Oshima Island (Nagasaki), which has operated since 1986 with 390 PV panels producing 10 m^3/day with dissolved solids (TDS) about 400 ppm.[40]

RESULTS

A solar-powered desalination unit produces potable water from saline water through direct or indirect methods of desalination powered by sunlight. Solar energy is the most promising renewable energy source due to its ability to drive the more popular thermal desalination systems directly through solar collectors and to drive physical and chemical desalination systems indirectly through photovoltaic cells.[1]

Direct solar desalination produces distillate directly in the solar collector. An example would be a solar still which traps the Sun's energy to obtain freshwater through the process of evaporation and condensation. Indirect solar desalination incorporates solar energy collection systems with conventional desalination systems such as multi-stage flash distillation, multiple effect evaporation, freeze separation or reverse osmosis to produce freshwater.[2]

Direct solar desalination

Solar stills

One type of solar desalination unit is a solar still, it is also similar to a condensation trap. A solar still is a simple way of distilling water, using the heat of the Sun to drive evaporation from humid soil, and ambient air to cool a condenser film. Two basic types of solar stills are box and pit stills. In a pit still, impure water is contained outside the collector, where it is evaporated by sunlight shining through clear plastic. The pure water vapor condenses on the cool inside plastic surface and drips down from the weighted low point, where it is collected and removed. The box type is more sophisticated. The basic principles of solar water distillation are simple, yet effective, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities, such as salts and heavy metals, and eliminates microbiological organisms. The end result is water cleaner than the purest rainwater.

Indirect solar desalination

Indirect solar desalination systems comprise two sub-systems: a solar collection system and a desalination system. The solar collection system is used, either to collect heat using solar collectors and supply it via a heat exchanger to a thermal desalination process, or to convert electromagnetic solar radiation to electricity using photovoltaic cells to power an electricity-driven desalination process.

Solar-powered reverse osmosis

Osmosis is a natural phenomenon in which water passes through a membrane from a lower to a higher concentration solution. The flow of water can be reversed if a pressure larger than the osmotic pressure is applied on the higher concentration side. In Reverse osmosis desalination systems, seawater pressure is raised above the natural osmotic pressure, forcing pure water through membrane pores to the fresh water side. Reverse osmosis (RO) is the most common desalination process in terms of installed capacity due to its superior energy efficiency compared to thermal desalination systems, despite requiring extensive water pre-treatment. Furthermore, part of the consumed mechanical energy can be reclaimed from the concentrated brine effluent with an energy recovery device.[1]

Solar-powered RO desalination is common in demonstration plants due to the modularity and scalability of both photovoltaic (PV) and RO systems. A detailed economic analysis [3] and a thorough optimisation strategy [4] of PV powered RO desalination were carried out with favorable results reported. Economic and reliability considerations are the main challenges to improving PV powered RO desalination systems. However, the quickly dropping PV panel costs are making solar-powered desalination ever more feasible.

A solar powered desalination unit designed for remote communities has been tested in the Northern Territory of Australia. The "reverse-osmosis solar installation" (ROSI) uses membrane filtration to provide a reliable and clean drinking water stream from sources such as brackish groundwater. Solar energy overcomes the usually high-energy operating costs as well as greenhouse emissions of conventional reverse osmosis systems. ROSI can also remove trace contaminants such as arsenic and uranium that may cause certain health problems, and minerals such as calcium carbonate which causes water hardness.[5]

Project leader Dr Andrea Schaefer from the University of Wollongong's Faculty of Engineering said ROSI has the potential to bring clean water to remote communities throughout Australia that do not have access to a town water supply and/or the electricity grid.[5]

Groundwater (which may contain dissolved salts or other contaminants) or surface water (which may have high turbidity or contain microorganisms) is pumped into a tank with an ultrafiltration membrane, which removes viruses and bacteria. This water is fit for cleaning and bathing. Ten percent of that water undergoes nanofiltration and reverse osmosis in the second stage of purification, which removes salts and trace contaminants, producing drinking water. A photovoltaic solar array tracks the Sun and powers the pumps needed to process the water, using the plentiful sunlight available in remote regions of Australia not served by the power grid.[6]

Solar photo voltaic power is considered a viable option to power a reverse osmosis desalination plant. The techno-economics both in standalone mode and in PV-biodisel hybrid mode for capacities from 0.05 MLD to 300 MLD were examined by researchers at IIT Madras. As a technology demonstrator, a plant of 500 litre /day capacity has been designed, installed and functional there.[7]

Energy storage

While the intermittent nature of sunlight and its variable intensity throughout the day makes desalination during nighttime challenging, several energy storage options can be used to permit 24 hour operation. Batteries can store solar energy for use at night. Thermal energy storage systems ensure constant performance at night or on cloudy days, improving overall efficiency.[8] Alternatively, stored gravitational energy can be harnessed to provide energy to a solar-powered reverse osmosis unit during non-sunlight hours

A concentrated solar still is a system that uses the same quantity of solar heat input (same solar collection area) as a simple solar still but can produce a volume of freshwater that is many times greater. While a simple solar still is a way of distilling water by using the heat of the sun to drive evaporation from a water source and ambient air to cool a condenser film, a concentrated solar still uses a concentrated solar thermal collector to concentrate solar heat and deliver it to a multi-effect evaporation process for distillation, thus increasing the natural rate of evaporation. The concentrated solar still is capable of large-scale water production in areas with plentiful solar energy.

Performance

The concentrated solar still can produce as much as twenty times more water than the theoretical maximum of a standard solar still[1][2] and in practice, can produce as much as 30x the volume.

A typically 25% efficiency standard solar still (not allowing for any recovery of rejected latent heat), as the latent heat of vaporization of water is 2.26 MJ per kilogram,[3] should evaporate 2.4 kg (or liters) of water per m^2 per day in a region with an average daily solar irradiation of 21.6 MJ/m^2 (250 $watts/m^2$), or 873 liters per year (like a precipitation height of 873 mm, 2.86 ft). A twenty times more productive still would have a daily output of 48 mm (1.9 in) or 17.5 m (57 ft) yearly.

Heat integration

Multiple stage evaporation

The concentrated solar still implements a method for recovering the latent heat of the distillate vapor not captured and reused by a standard solar still. This is done by using multiple stages of evaporation in series (see multiple-effect evaporator). The latent heat of the distillate vapor produced in the n-1 stage (or effect) is recovered in the nth stage by boiling the leftover concentrated brine from the n-1 stage which produces distillate vapor whose latent heat will be recovered in the n+1 stage by boiling the leftover concentrated brine from the nth stage.[4] Since brine is continuously concentrated in each stage, its boiling point will continue to rise under standard conditions. To overcome the boiling point elevation of the brine, each evaporator stage operates at a lower pressure than the previous stage, which effectively reduces the boiling point, allowing for sufficient heat transfer to take place in each stage. This process can be repeated until the distillate conditions are sufficiently degraded (i.e., pressure and temperature are very low and the distillate vapor volume is very large).[4]

Heat pump

The final evaporation stage produces distillate vapor that is considered to be at very poor state conditions. This vapor can either be condensed in a final condenser, in which case its latent heat will be shed as waste,[5] or it can be condensed by using a heat pump, in which case its latent heat (or a portion of it) can be recovered. In the latter case, the heat pump effectively "upgrades" the state conditions of the latent heat to more usable conditions (higher temperature and pressure) by performing work (e.g., compression).[1][2] The conditions can be sufficiently upgraded such that the recovered heat can be used to provide additional heat for evaporation in the first effect.

CONCLUSION

A completely passive solar-powered desalination system developed by researchers at MIT and in China could provide more than 1.5 gallons of fresh drinking water per hour for every square meter of solar collecting area. Such systems could potentially serve off-grid arid coastal areas to provide an efficient, low-cost water source.[23]

The system uses multiple layers of flat solar evaporators and condensers, lined up in a vertical array and topped with transparent aerogel insulation. It is described in a paper appearing today in the journal Energy and Environmental Science, authored by MIT doctoral students Lenan Zhang and Lin Zhao, postdoc Zhenyuan Xu, professor of mechanical engineering and department head Evelyn Wang, and eight others at MIT and at Shanghai Jiao Tong University in China.

The key to the system's efficiency lies in the way it uses each of the multiple stages to desalinate the water. At each stage, heat released by the previous stage is harnessed instead of wasted. In this way, the team's demonstration device can achieve an overall efficiency of 385 percent in converting the energy of sunlight into the energy of water evaporation.[28]

The device is essentially a multilayer solar still, with a set of evaporating and condensing components like those used to distill liquor. It uses flat panels to absorb heat and then transfer that heat to a layer of water so that it begins to evaporate. The vapor then condenses on the next panel. That water gets collected, while the heat from the vapor condensation gets passed to the next layer.

Whenever vapor condenses on a surface, it releases heat; in typical condenser systems, that heat is simply lost to the environment. But in this multilayer evaporator the released heat flows to the next evaporating layer, recycling the solar heat and boosting the overall efficiency.

"When you condense water, you release energy as heat," Wang says. "If you have more than one stage, you can take advantage of that heat."[30]

Adding more layers increases the conversion efficiency for producing potable water, but each layer also adds cost and bulk to the system. The team settled on a 10-stage system for their proof-of-concept device, which was tested on an MIT building rooftop. The system delivered pure water that exceeded city drinking water standards, at a rate of 5.78 liters per square meter (about 1.52 gallons per 11 square feet) of solar collecting area. This is more than two times as much as the record amount previously produced by any such passive solar-powered desalination system, Wang says.

Theoretically, with more desalination stages and further optimization, such systems could reach overall efficiency levels as high as 700 or 800 percent, Zhang says.

Unlike some desalination systems, there is no accumulation of salt or concentrated brines to be disposed of. In a free-floating configuration, any salt that accumulates during the day would simply be carried back out at night through the wicking material and back into the seawater, according to the researchers.[31]

Their demonstration unit was built mostly from inexpensive, readily available materials such as a commercial black solar absorber and paper towels for a capillary wick to carry the water into contact with the solar absorber. In most other attempts to make passive solar desalination systems, the solar absorber material and the wicking material have been a single component, which requires specialized and expensive materials, Wang says. “We’ve been able to decouple these two.”

The most expensive component of the prototype is a layer of transparent aerogel used as an insulator at the top of the stack, but the team suggests other less expensive insulators could be used as an alternative. (The aerogel itself is made from dirt-cheap silica but requires specialized drying equipment for its manufacture.)

Wang emphasizes that the team’s key contribution is a framework for understanding how to optimize such multistage passive systems, which they call thermally localized multistage desalination. The formulas they developed could likely be applied to a variety of materials and device architectures, allowing for further optimization of systems based on different scales of operation or local conditions and materials.

One possible configuration would be floating panels on a body of saltwater such as an impoundment pond. These could constantly and passively deliver fresh water through pipes to the shore, as long as the sun shines each day. Other systems could be designed to serve a single household, perhaps using a flat panel on a large shallow tank of seawater that is pumped or carried in. The team estimates that a system with a roughly 1-square-meter solar collecting area could meet the daily drinking water needs of one person. In production, they think a system built to serve the needs of a family might be built for around $100.

The researchers plan further experiments to continue to optimize the choice of materials and configurations, and to test the durability of the system under realistic conditions. They also will work on translating the design of their lab-scale device into a something that would be suitable for use by consumers. The hope is that it could ultimately play a role in alleviating water scarcity in parts of the developing world where reliable electricity is scarce but seawater and sunlight are abundant.

“This new approach is very significant,” says Ravi Prasher, an associate lab director at

Lawrence Berkeley National Laboratory and adjunct professor of mechanical engineering at the University of California at Berkeley, who was not involved in this work. “One of the challenges in solar still-based desalination has been low efficiency due to the loss of significant energy in condensation. By efficiently harvesting the condensation energy, the overall solar to vapor efficiency is dramatically improved. … This increased efficiency will have an overall impact on reducing the cost of produced water.”

The research team included Bangjun Li, Chenxi Wang and Ruzhu Wang at the Shanghai Jiao Tong University, and Bikram Bhatia, Kyle Wilke, Youngsup Song, Omar Labban, and John Lienhard, who is the Abdul Latif Jameel Professor of Water at MIT. The research was supported by the National Natural Science Foundation of China, the Singapore-MIT Alliance for Research and Technology, and the MIT Tata Center for Technology and Design.[32]

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IJTSRD International Journal of Trend in Scientific Research and Development ISSN: 2456-6470