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Perspectives on solar distillation: a review

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ABSTRACT

An investigation has been made to develop a robust solar water purification system for remote areas without potable water or energy. Many stills have been studied, but few are practical due to low efficiency and water yield. A study of the global water supply and existing treatment methods has been made to understand the problem and to develop the design. Further analysis should lead to an apparatus that can supply potable water in remote, water- or energy-deprived areas with minimal maintenance and long-term cost.

Objectives for simple still design have been identified, as well as drawbacks in current designs. Employing active techniques such as spray evaporation, baffling, vacuum distillation, forced convection, separate chambers and membrane distillation are shown as areas of potential yield improvement.

1. INTRODUCTION

The absolute dependence of life on the availability of water is becoming more apparent as environmental pressure mounts. Yet only three percent of the Earth's total water supply is fresh water, and much of that is in the polar ice caps, or inaccessible below the earth's surface. Only about one-hundredth of a percent is easily available. Nevertheless, there are 4 300 000 cubic kilometres of useable fresh water in the ecosystem of varying distribution and quality (World water facts, 2002).

Environmental campaigners have repeatedly warned that the Earth's water resources are finite. According to the World Health Organisation, 80% of diseases in developing nations stem from unsafe water, killing more than 25,000 people each day. The world's demand for water from 1900 to 1995 increased sixfold, more than twice the rate of population growth. The UN estimates that if present trends continue, in less than 25 years, 5 billion people will find it virtually impossible or difficult to meet the very basic water needs for sanitation, cooking and drinking (World water facts, 2002).

In general, safe water availability is linked to economic status. Water quality has improved over the last 20 years in most industrialised countries, mainly due to increased sewage treatment. The biggest threats are from industrial and chemical pollution, especially agricultural run-off. England has 41,500km of rivers, however only 2,700km have good quality water suitable for drinking (Walker, 1992). Ideally, unpolluted groundwater is the best source, however more than half the population of OECD countries and over 70 % of the USA drinks water that has been through wastewater treatment plants (OECD, 1993). The danger is that not all impurities may be removed, and the chemical agents used in treatment may themselves pose health risks.

In developing countries, especially around urban areas, water quality is generally deteriorating. Approximately half the Third World population is still without safe drinking water. The greatest difficulties are the cost of piping, and protecting water supplies from sewage pollution. For example, out of 3,119 towns and cities in India, only 217 have partial or complete sewage treatment facilities. Of 78 rivers monitored in China, 54 are "seriously polluted" with untreated sewage and industrial wastes (Sivakumar, 1997). Twenty-six countries containing 232 million people already face water scarcity. The Middle East is the worst region; observers predict that water - not oil – may spark future wars (Gleick, 1992).

Some ecosystems are already under severe stress and climate change is predicted to make things worse. The long list of natural areas destroyed or at grave risk from increased water extraction includes the Florida Everglades and California's Mono Lake in the USA, the Donana wetlands in Spain, the Sudd swamps in the Sudan, the Okavango Basin in Botswana, and the Aral Sea, in the former USSR (Sivakumar, 1997). Extraction is not the only problem; areas that receive run-off are threatened too. Wildlife in California's Kesterton wetland was devastated when selenium from irrigation water passed safe levels. Only the die-off alerted authorities to the problem (Qashu, 1995).

All natural water is impure in some way due to the environment it permeates through. It can harbour pathogens, protozoa, viruses and other organisms. There are treatment options available but they are limited by limited effectiveness against some types of pollutants, the energy required to run them and their cost of implementation. Reliable, cost-effective methods are needed to supply potable water without further degrading the environment. Sustainable development through renewable energy sources is the goal.

Distillation and reverse osmosis are the only known processes that will effectively remove microbes, turbidity, sediment, colloidal matter, total dissolved solids, toxic metals, radioactive elements, pesticides and herbicides. Seawater is capable of supplying the world's water needs. Energy for distillation can be provided by the sun. Investigating an effective solar desalination distiller is the core of this paper.

2. OBJECTIVES

The design of next generation solar stills requires the following important characteristics:

- High efficiency;
- Large capacity of one unit and/or a group of units;
- Self-sustainable performance at any place, using only solar energy;
- A long life span;
- Simple operation and maintenance;
- No special materials required for production and maintenance;
- Environmentally tough and friendly system.

Distillation and reverse osmosis can remove all water contaminants. Both can use any water source and, while reverse osmosis requires less energy during operation, its set-up costs are significantly higher. The disadvantages of distillers are their initial costs and the slowness of the process. Most stills produce about 3 litres per hour. Like reverse osmosis, they require around 5 litres of water to produce 1 litre of pure water (Archer, 1991). Desalinated water is also 'flat' (lacking in dissolved oxygen and carbon dioxide) and in certain essential elements. This is solved by re-aeration of the distilled water and 'seeding' with a small amount of salt (up to 0.5% the value of seawater) to improve taste (Porteous, 1983).

Manwell and McGowan (1994) investigated renewable energy driven desalination in multi-stage flash distillation, freeze separation, vapour compression, electro-dialysis and reverse osmosis. Discussion from here will centre on solar distillation and the improvements being made to increase the efficiency and effectiveness so it can compete with other techniques.

3. SOLAR STILLS

Carlos Wilson designed the first solar still in Las Salinas, Chile in 1872. This simple basin-type still produced around 4.9 litres per square metre per day. The basic design is shown in Figure 1. Solar distillation is attractive for producing potable water using 'cost-free' solar energy. The energy can be used directly for evaporating water inside a 'solar still', or indirectly by converting it to a form suitable for operating other desalination processes, e.g. thermal evaporation, reverse osmosis or electro-dialysis.

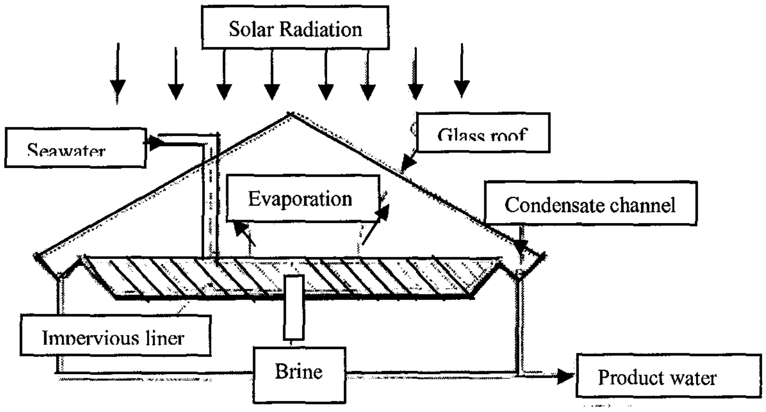

Figure 1: Design of a simple solar still (Duffie & Beckman, 1991)

The sun's energy passes through the transparent glass cover and is absorbed by the water via the basin liner. Losses include reflection from the glass cover and water surface, absorbance by the still materials and heat lost through the bottom. The water warms then heat exchange occurs between the water and glass cover by radiation, convection and evaporation. The evaporated water condenses on the glass cover, releasing its latent heat. The condensed water trickles down under gravity until it is collected in internal gutters leading to a drainage hole at the end of the condensing cover. Basins are usually made of concrete and lined with rubber sheets or coated with black paints resistant to sea- or brackish water. Any material that has a high radiation absorbance, corrosion resistance and low cost is suitable.

Efforts to improve yield have concentrated on improving either the design or the operating conditions. Using appropriate insulating materials, selecting cheap materials for the black liner (Madani and Zaki, 1995), optimising glass tilt angles, adjustment of the brine level (Singh and Tiwari, 1993) and flushing frequency are among the parameters studied. During the past 20 years unique stills have been developed, such as multi-effect stills (Assouad and Lavan, 1988), double-roof stills (El-Bahi and Inan, 1999), double condensers (Tiwari et al, 1997), diffusion stills and wetted wick stills (Tiwari et al, 1994). Coupling solar stills to external assisting systems, such as flat-plate collectors (Zaki et al, 1993), concentrators (Garcia-Rodriguez and Gomez-Camacho, 1999), heat pipes, waste-heat sources, vapour-condensing coils, cooled condensers (Abu-Hijeg and Mousa, 1997) and packed column condensers (Anon, 1983) have been investigated as a means to improve the performance. Unfortunately none of these designs has yet made solar distillation attractive commercially. A taxonomy of development is shown in Figure 2.

The focus now is to improve the economy, either by using cheap durable materials, or by improving the distillation rate to supply niche markets, especially in isolated areas. The cost of water produced by conventional direct solar distillation is estimated at US\$2.13~3.60/m^3. Experience in Rajastan, India reported a cost of US\$3.75/m^3. The present estimate shows clearly that solar distillation, even using cheap materials and eliminating some of the basin structure, cannot be less than US\$1/m^3. The best estimate is \$2.40/m^3 (Madani and Zaki, 1995). The installation cost is the determining factor in solar distillation economics as the operation and maintenance costs are relatively small. Many existing distillation plants do not

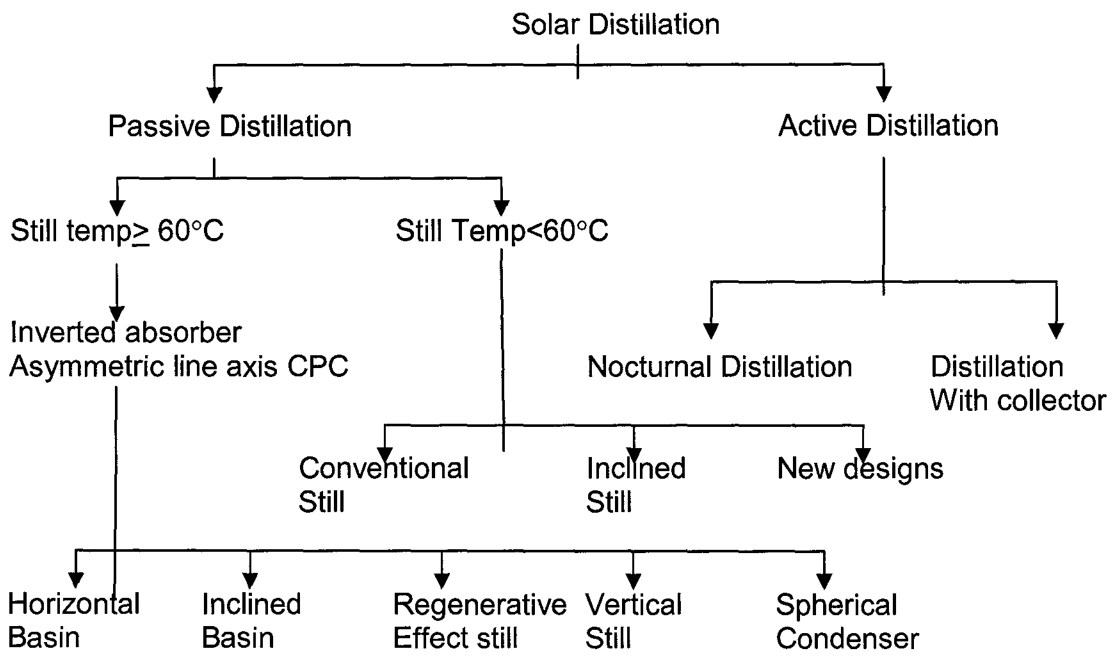

Figure 2: Taxonamy of solar distillation development (Tiwari et al, 1994)

meet expected outcomes because of the need for maintenance. Commonly there is no built-in arrangement for basin cleaning, no provision for algal removal, sealant materials used do not prevent vapour leakage through joints/corners and cleaning of the glass cover is not carried out frequently.

Despite the vast amount of work to improve the passive solar still it is still hampered by low yields that make it commercially unacceptable. Rahim (2001) identified some of the reasons for these drawbacks, including:

- The water surface intercepts less energy than is transmitted through the glass cover.
- A large mass of water with a fixed amount of heat means lower evaporation rates.
- Nocturnal production is low, if not zero.
- Insufficient temperature gradients between the water surface and glass condenser.
- Water condensing on the glass stops incoming radiation.
- Natural convection doesn't deliver all the evaporated water to the condenser.
- Condensed drops on the glass can fall back into the basin.
- Condensed drops can re-evaporate, both from the glass and the collection channel.

Solar still designers must recognise the need for smooth, coupled heat and mass transfer. Heat transfer requires a source and a sink, somewhere for the heat to be dissipated. In a passive simple still the cover acts as both the source and the sink, a heat and mass transfer 'bottle-neck' that results in low yield. The future of solar distillation lies in a more active approach, especially if a high rate distiller to meet the increasing needs of society is ever to be developed. There are a number of high-rate principles that are beginning to be incorporated into solar desalination systems to increase their productivity. They include spray evaporation and related steam flash distillation, baffling, vacuum distillation, forced convection and separate condensation chambers.

3.1 Spray Evaporation

Evaporation area can be increased either by using a fabric, wick or some kind of high surface material like sponges or thorn bushes. Another possibility is to spray the salt solution into air and then condense the moistened air. Total surface area doubles as drop radius halves. Tests have shown that heat transfer improves appreciably when the evaporative surface is covered by only a thin film of liquid. This is because the hydrostatic pressure no longer suppresses boiling, and the vapour can escape from the liquid more readily (Steinbruchel and Rhinesmith, 1980). In sprayed drops the hydrostatic pressure is directly proportional to the drop diameter, which is considerably less than the dimensions of a passive solar still. Kwatra (1996) suggests that an increase in distillation of up to 30.2% can be made if the available evaporation area is increased to three times the receiver area in a simple solar still.

Joyce et al (1994) tested a device with two concentric cylindrical chambers that communicate on the top and bottom. The heated solution is sprayed into the top of the inner chamber (the evaporation chamber) by a nozzle. This increases the surface area for evaporation and humidifies the air. Air circulates by free convection through the top to the outer chamber (the condensation chamber) where it condenses around a helical pipe producing the distilled water. Figure 3 shows their apparatus.

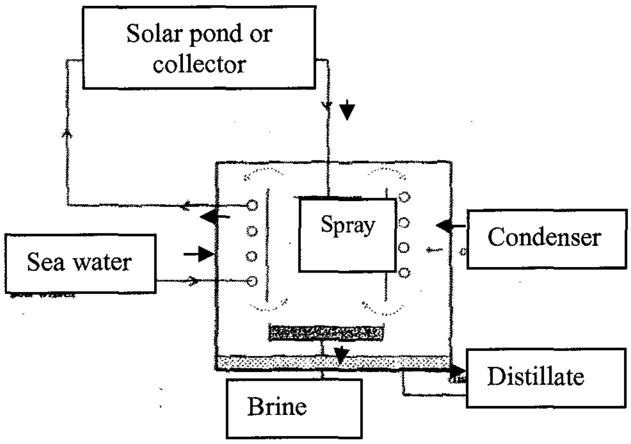

Figure 3: Spray-type evaporator (Joyce et al, 1994)

Drop diameters are important in the production and conversion rate. This means lower flow rates are needed at high pressure to obtain small drops. Film and spray evaporators have the advantages of high heat transfer at lower temperatures with reduced losses, lower costs and allow easy reuse of the latent heat of condensation. The theoretical value of maximising the surface area for evaporation is clearly seen, but needs more research to produce a useable system.

3.2 Steam Flash Distillation

Steam flash distillation builds on spray evaporation but incorporates a pressure differential as well. Pressurised water is heated in the collector and then flashed to steam in a separate vessel, which acts as a steam separator. The vertical flash vessel has the water inlet located about one-third of the way up its side. The vessel diameter is chosen so that the steam flows towards the top outlet at no more than 3 m/s. This ensures that any water droplets fall through the steam, rather than being carried with it. This is important since carrying the droplets to the condenser before the seawater can evaporate short-circuits the distillation and contaminates the distillate. Adequate height above the inlet is necessary to ensure separation; a downward pointing spray also helps. The diameter and height of the vessel to ensure separation were determined as 65 and 600mm respectively (Kalogirou et al, 1994). Parabolic trough collectors are attached to the system. These are often used for steam generation because temperatures of about 300°C can be obtained without serious losses in the collector efficiency.

All solar stills suffer from the start-up and slow-down that naturally accompanies the solar cycle. Minimising start-up energy requirements to maximise output is the goal. The system is refined by optimising the flash vessel water capacity, dimensions and construction to lower the thermal capacity and losses. One constraint is the fixed mass of water circulating in the pipes. Over-sizing the flash vessel to increase storage has the advantage of a higher starting temperature in the morning but requires more water to be heated up. The optimal volume is 0.7 litres.

3.3 Baffling

The effect of baffles to optimise fluid flow is well covered in other fields but its importance to distillation is only just being recognised. Bemporad (1995) examined a thermohaline saltwater column common in distillation. The chamber is subject to thermal and mechanical energies, salt and water through brine movements and evaporation. It is well known that an increase in evaporation decreases the surface temperature, while an increase in surface salinity due to evaporation decreases further evaporation. These differences in temperature and salt concentration all affect the column's stability. He concluded that a proper configuration of baffles and inlet and outlet pipes is needed to prevent the unnecessary mixing of the water so that the warmest water was retained near the surface to drive the evaporation process. The evaporation rate is also a function of the quantity of gases dissolved in the seawater (Kennard, 1938). An unsteady heat source is also likely to cause extra mixing. Heat is lost more rapidly from the surface than salt, so the density of the layer increases until it becomes unstable. Directly applying a solar panel to the seawater chamber does not seem to offer maximum efficiency unless energy storage mechanisms (such as a solar pond) are introduced.

3.4 Vacuum Distillation

Vacuum distillation of seawater has been researched in both in the direct and coupled configurations. Nishikawa et al (1998) developed a solar-distillation system to yield fresh water without using energy from fossil fuels. The still was coupled with a 7.8 m^2 solar collector and 3.7 m^2 of solar cells to provide power for a vacuum pump. The system produced up to 73.6 kg of fresh water per day. The total latent heat of the distillation was 1.7 times the solar radiation since the solar energy was used three times at temperatures between about 5 and 40°C. Power consumption by the vacuum pump was only 1.17 MJ/day while the solar cells generated 3.43 MJ/day. A sketch of the system is provided in Figure 4.

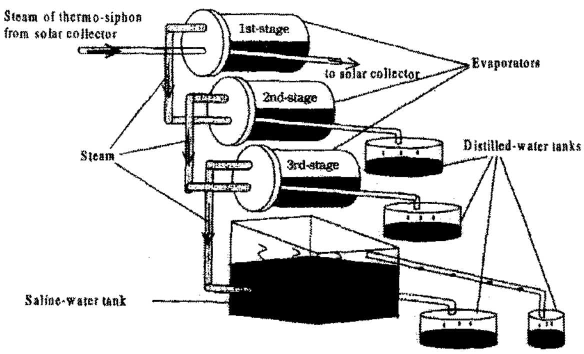

Figure 4: Sketch of triple effect evacuated solar still, (Nishikawa et al, 1998)

A thermosiphon system was introduced into the solar collector. The heat transfer medium is pure water and the air in the solar collector was evacuated using a vacuum pump. At any temperature, water evaporates and transfers the solar thermal energy to the first evaporator. After condensing in the evaporator, pure water comes back to the solar collector by gravity. Using the vacuum pump not only achieves distillation at low pressures in the evaporators and the solar collector, but also removes dissolved gases in the seawater. The vacuum pump can be used to draw water into the system instead of a pump.

Hussaini and Smith (1995) compared a conventional solar still under normal and vacuum conditions. They showed an increase of more than 100%. In winter days, the produced water without vacuum was 1.45L/day, increasing to 3.39 L/day with the vacuum. In summer, it was 8.07 L/day compared to 3.79 L/day without. The increase in productivity is mainly due to the absence of convection heat transfer loss from the water and lack of non-condensable gases inside the still. Convection losses reduce the water temperature and increase the glass temperature, reducing evaporation and, hence, productivity. Convective heat transfer is about 8% of the total solar radiation so the absence of non-condensable gases is important. Non-condensable gases such as air greatly reduce the heat transfer co-efficient for condensation. When the vapour containing non-condensable gases condenses, the non-condensable gas is left at the surface. The vapours that follow must diffuse through this vapour-gas mixture before reaching the condensing surface. The condensation heat transfer coefficient is reduced by 50% or more with a few per cent decrease in the volume of air.

Also, air between the water and glass surfaces acts as a resistance to vapour motion. The resistance to the diffusion process causes a drop in the partial pressure of the vapour, which, in turn, drops the saturation temperature. Water temperature in the case of vacuum is slightly lower than the water without vacuum. This is due to greater evaporation; but at the same time, the lower temperature causes less radiation heat loss, increasing the water temperature. Generally, the difference in water temperature with and without vacuum is small. The same is true for the glass temperature.

Wastewater has been successfully treated using an enhanced variable vacuum distillation system. The liquid is degassed under an intense vacuum to remove volatile organic compounds before being distilled under a vacuum using mechanical vapour recompression. It removes virtually all contaminants such as TSS, TDS, BOD, COD, heavy metals and mineral compounds (MacCabe, 1999). This vacuum pre-treatment overcomes the problem distillation has in separating pure water from volatile substances which have a lower boiling point. Pre-treatment also removes non-condensable gases such as oxygen and carbon dioxide, which inhibit condensation, and also removes hydrogen sulphide, which is corrosive to copper alloys (Steinbruchel and Rhinesmith, 1980).

3.5 Forced Convection

Most stills operate under natural convection, the principle that hot air rises and cold air sinks. Forced convection uses artificial means to promote air movement. Rahim (2001) constructed a simple still fitted with a forced convection condenser. A small solar powered fan drew air from near the glass cover through a copper pipe condenser that passed through the basin. Use of forced convection improved the efficiency from 19% to 31%. Bacha et al (2000) modelled a desalinator using a cooling tower arrangement and found that productivity was increased more by higher air movement than by water mass velocity.

3.6 Separate Condensation Chambers

Separating the evaporating and condensing zones gives greater control over the temperature gradients. Condensation is directly proportional to this difference. Simple stills show a temperature gradient of up to 6 degrees. The first author produced a design in 2000 with a gradient of only 1 degree. Though the basin temperature exceeded 70 °C at times, no production resulted because the condenser was too hot (Scott, 2001). It appears that the major problem with stills is not energy capture, but energy dissipation. Water-cooled condensers that recover the latent heat of condensation are recommended for further study (Abu-Hijeg and Mousa, 1997). Rahim (2001) produced a system with a gradient of 50 degrees however its effect on production rates was not quantified. Haddad (2000) coupled a cooling panel to a packed-bed condenser separated from a solar still to utilise radiative effects.

4. CONCLUSION

The basic design for simple distillation has benefits in ease of construction and lower costs however the low production rates have prevented it from wide-scale use. Drawbacks such as incomplete maintenance, algal and scale build-up and sealant leakages are problems, particularly where the users have low technical skills. Thermodynamic and heat transfer problems such as the back wall absorbing incident radiation, excess water inventory inhibiting evaporation, negligible nocturnal production, lack of temperature gradients for condensation, condensed drops blocking radiation or being re-evaporated and ineffective convection must be solved before simple distillation can fulfil its potential to meet the water needs of an increasingly dry earth. Employing more active techniques such as spray evaporation, baffling, vacuum distillation, forced convection and separate chambers have been shown as areas of potential improvement.

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