Solar Water Purification at Night: design of a suitable heat pump

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Abstract. This paper is about a method to enhance solar water still productivities we build on previous efforts by the Solar Engineering team at our university and on those by others elsewhere, to introduce a design that enables sustained solar distillation even in cloudy and night time conditions. Water is a most essential requisite for life as we know it on this planet. It plays a crucial role in the welfare of societies around the globe and affects the sustenance and stabilization of every living thing. However, despite the fact that it covers 70% of the Earth’s surface, only 2.5% of what is available, is suitable for human consumption. The balance 97.5% is either too salty or too contaminated. Even the 2.5% can be subject to micro-bio contamination during the collection, distribution and storage stages. It is therefore imperative to decontaminate it before drinking it. Because previous work on solar water purification relied only on the thermal effect of sunlight, it suffered serious loss of productivity during cloudy and night time conditions. Also, the purifiers had big thermal inertias because of the high specific heat capacity of water, leading to delayed onset of distillation when the sun reappeared. In the present work, we address these problems by use of supplementary heating from stored solar energy in form of electricity, but this time enhanced by the heat pump effect of refrigeration systems. Moreover, the design introduced, significantly lowers the top glazing temperature, increasing distillation rate, while also reducing energy losses to the atmosphere. Preliminary results from the prototype show a more than 100% rise of daily pure water collection at a heat pumping coefficient of performance varying between 2.3 and 4.1. It is concluded that this is a significant contribution to the technology of solar water purification.

1. Introduction
Water is one of essential needs of life on Earth. It plays a pivotal role in the welfare of societies around the globe and affects the sustenance of every human. It is the most spread substance that covers more than 70% of the earth surface. However 97.5% of that amount is salty water, leaving only 2.5% as consumable water which can be found in deep underground aquifers or as soil moisture and the large amount of that fresh water represent about 70% is confined in the glaciers [1].

In recent decades, massive growth in population and modern life has led to significant expansion in agricultural and industrial production. Africa for instance has the highest population growth in the world at 3.9% per year and by 2030 Africa urban population is expected to reach up to 654 million people [2]. The associated increase in energy demands and the generation of waste have increased the pressure on the water resources, oceans and seas. These activities have led to destabilization of natural ecosystems and deterioration of water supply systems [3].
Recent researches and studies on potable water warn that freshwater sources are becoming scarce and most countries are suffering from water contamination due to climate change, human activities and long-term droughts. Some regions such as India, China, north and sub Saharan Africa and the Middle East are the most affected according to the studies prediction. By 2050, world population is expected to reach up to 9 billion and therefore, the demand on fresh water will increase and put more pressure on freshwater resources[4] [5].

The difficulties of access to utility grid in rural African areas for instance have led the dwellers to depend on biomass as a source of energy for their life purposes. A survey on households of selected countries in sub Saharan Africa indicated that 25% of households in all seven countries have access to the electricity and more than 66% depend on biomass to serve their needs [6]. Activities such as cooking, heating and water boiling require considerable amounts of energy and therefore, more trees are being cut. This is causing huge damage to the environment representing in desertification and drought.

Despite the fact that water and energy are correlated, the energy deficit in the mentioned regions makes the equation unbalanced. Also, drinking water resources such as rivers, lakes and natural springs are exposed to variety of atmospheric conditions that affect its quality and therefore some form of treatment has to be applied to make it suitable for human consumption [7]. Providing communities with adequate drinking water has become a challenge to governments and it is draining the economies. Therefore, using alternative source of energy to treat water is a promising solution in terms of profitability and government organizations commitments, and more importantly raise public health concern. Solar water distillation technologies which we addressed in this research are the most effective and convenient methods of water treatment for rural areas.

2. Water Quality and Public Health

From a scientific perspective, water has a molecular weight of 18. It has a simple structure with two hydrogen atoms and an oxygen atom. The molecules are further interlinked together with hydrogen bonds. This gives water unique features (large latent heat for phase changes, heat capacity and good solvent) to behave differently compared with other compounds of similar molecular sizes [8]. It also makes it more difficult to heat and to purify.

The term water quality could be used to describe the suitability of water for human consumptions and health ecosystem. It describes the biological, chemical and physical characteristics of water. The biological constituent (living organisms) includes viruses, bacteria, phytoplankton, protozoans, insects and plants. The most common chemical constituent (dissolve substances) includes gases (e.g., oxygen, oxide of nitrogen and carbon dioxide), metal (e.g., iron and lead), pesticide (e.g., atrazine and endosulfan) and other organic compounds. While physical characteristics of water include taste, colour, odour, temperature and turbidity [9].

Water quality standards are determined by authorized organization and governments. World Health Organization (WHO) for example has established guideline for drinking water standards. It suggests that it should be legal international standards for drinking water quality in all countries [10] [11].

In terms of health sector, waterborne diseases contribute high rates of mortality and morbidity after respiratory infections. It is estimated that more than 60 million cases of gastrointestinal infection occur annually [12] and causing death for about 1.8 million children [13]. The most common health hazards associated with water contamination are those infectious diseases caused by pathogenic bacteria and viruses. Chemical contamination of drinking water has less impact on human health than microbial contamination. Its effects appear after prolonged period of consumption, but there are some hazards associated with massive leakage of chemical to the water supply [10].

3. Solar Distillation

The first practical application to obtain potable water using solar energy was designed and developed in 1872 by Swedish engineer Carlos Wilson. The purifier units were providing miners and their families with fresh water. The unit structure was made from wood and timber, and covered with a
glass sheet [14]. Figure 1 shows single slope solar still. It is considered as a most common design reliable for homestead rural areas for drinking purposes. It consists of airtight trapezoidal basin constructed from galvanized iron sheets, aluminum or reinforced plastic, covered with transparent plastic or glass sheet. The bottom surface of the basin is blackened to increase its absorptivity to solar radiation. At the lower end of the transparent cover there are channel runs through it to collect the distilled vapor. The brackish or saline water can be fed to the still throughout the inlet valve. For purposes of cleaning, the sill is provided with drainage system. All side walls and the bottom are insulated. During shiny days, the temperature inside the still can reach up to 80°C evaporating the brackish water. The resulting vapor condenses at the transparent cover then sliding to the channel at the lower end collecting outside the still as drinkable pure water. The long term period of exposure to sun light and high temperature range are sufficient to eliminate most of contaminants includes the pathogenic germs. Bacteria for example die between 40 and 100°C, Protozoa and Fungi die between 40 and 60°C [15].

Figure 1. Conventional single slope solar still

4. Advanced Solar Still
The conventional solar still mentioned above requires solar radiation to operate. During a cloudy days or early morning hours, these kinds of stills cannot produce purified water because of low water temperatures in them. Therefore, in this research, we address the problem by introducing a more advanced solar still that uses a vapour-compression heat pump as both a preheater and a backup system. Figure 2 shows the schematic diagram of the advanced solar still. It consists of an airtight trapezoidal aluminium basin with a top cover of double transparent plastic sheets of 1mm thickness. A 10mm gap left between the sheets allows water to circulate. And cool the inner glazing, thereby increasing the condensation rate on the glazing while transferring the heat back to the refrigerant that will recirculate it to the water through the condenser. Two channels mounted at the lower end of the cover, collect circulated water and distilled water. Two auxiliary systems were attached to the still. The first one is a vapour compression heat pump system where the condenser attached close to the bottom of the basin. The evaporator installed to the side wall of the cooling compartment. The walls of the cooling compartment were made from three layers of plastic, insulation and aluminium. A DC compressor runs the heat pump. The second system is water circulation system. A circulation pump is used to pump the cold water from the cooling compartment to the channel between the double glazing covers in order to cool down the inner surface of the cover to increase the condensation rate. Composite pipes were used to increase corrosion resistance. A small PV system is used to power the purifier.
5. Theoretical analysis

This section discusses the methods used to determine the total thermal energy efficiency and the coefficient of performance of the vapour compression heat pump (COP).

5.1. Thermal energy efficiency

During the sunny days, the total solar radiation received at the still’s cover $I_0(t)$. A fraction of it is reflected by the cover $R_c I_0(t)$, the transmitted fraction inside the basin of the still $\tau_c I_0(t)$ part of it is reflected $R_w I_0$ and absorbed $\alpha_w I_0$ by the water. Then, the rest of solar radiation reaches the blackened surface of the still. At this point most of the thermal energy is convected to the water and small fraction is conducted to the atmosphere. Here, it is assumed that all the absorbed solar radiation is harnessed for evaporation and thermal losses therefore, the energy balance equation can be written as:

\[
[\alpha'_w + \alpha'_b] I_0 A_s = m_w L + U'_L (T_w - T_a) A_s
\]

where, $\alpha'_b$ is solar flux absorbed by blackened surface, $\alpha'_w$ is solar flux absorbed by water mass, $U'_L$ is the overall heat transfer coefficient from water to ambient. L is latent heat of vaporisation.

The overall thermal efficiency of the still can be written as:

\[
\eta = \frac{\sum m_w L}{A_s \int I(t) \, dt} \times 100
\]

The latent heat of vaporisation $L$ for operating temperature lower than 70 °C can be calculated as

\[
L = 3.1615 \times 10^6 (1 - 7.616 \times 10^{-4} T)
\]

For temperature higher than 70 °C,

\[
L = 2.4935 \times 10^6 (1 - 9.4779 \times 10^{-4} T + 1.3132 \times 10^{-7} T^2 - 4.7974 \times 10^{-9} T^3)
\]
5.2. Heat pump efficiency
The efficiency of the vapour compression heat pump cycle can be estimated by applying the first law of thermodynamic to each process of the cycle. Therefore, the COP is expressed as:

\[ \text{COP} = \frac{Q_H}{W} \]  

\[ W = \dot{m}(h_2 - h_1) \]  

\[ Q_H = \dot{m}(h_2 - h_3) \]

Here, \( \dot{W} \) compressor input power (W), \( \dot{m} \) is mass flow rate of the refrigerant (kg/s), \( h \) is enthalpy (kJ/kg).

6. Experiment setup and methodology
Water-to-water vapor compression heat pump system was designed and sized to match the water purifier configuration as described in section 4. In order to ensure long lasting for the purifier, good materials been selected to build it. Simplicity in system layout is considered as well.

For purpose of experimentation, the conventional and advanced solar stills were tested to compare their performances under the same weather conditions. The stills were mounted close to the Campbell Scientific weather station, so they could be exposed to the similar weather conditions registered by the station. The experiments were carried out under the atmospheric conditions at the top roof of mechanical department building, Bellville, Cape Town. The data collection was done during the day starting from 8:00 to 17:00 during the month of May 2019.

\[ \text{Figure 3. The experiment setup} \]

During the period of experimentation, solar radiation intensity, wind speed and ambient temperature were collected from the weather station which consists of two pyranometers and an anemometer. A pyranometer with shading ring measures diffuse radiation. The other one for
measuring the total solar radiation (diffuse and beam). The anemometer measures the wind speed. All of them are connected to the data logger. Sets of thermocouples were attached inside the basin of each still, another sets were attached to the vapor compression heat pump system to test its thermal efficiency. Graduated containers were used to measure the amount of purified water. The layout of the equipment and the instrumentations are shown in figure 3.

7. Results and discussion
The data collection of the experimentations is continued for the first two weeks of May 2019. A lot of data was collected in order to compare between the two solar stills. In this section we presented the results of the experimentations of the stills on semi cloudy days so that we indicated the performance of the stills in critical conditions. The results were as following:

The variation of the water temperature inside the stills and the ambient temperature are shown in figure 4. From the graph, we can notice that the heat pump system reduced the time required to heat up the water to operating temperature and it increased water temperature up to 66 °C. Figure 5 shows the vapour temperature of each still. We can notice from the graph that the double glazing of the advanced still maintained the heat inside and the fraction escaped from the first cover is recovered by circulated cold water and the heat pump transferred again inside the still.

Figure 4. Variation of water temperature inside the stills

Figure 5. The deference between the vapor temperatures of each still
The coefficient of performance (COP) of the vapor compression heat pump is shown in figure 6. The COP varies between 2.3 to 4.1

![COP graph showing the coefficient of performance for a vapor compression heat pump.](image)

**Figure 6.** The coefficient of performance (COP) of the vapor compression heat pump

The amount of water produced by each still and the maximum temperature of outer surface of the glazing are indicated in table 1.

| Table 1. Stills performance |
|----------------------------|
|                            |
| Conventional still         | Advanced still |
| Water production(L/m²)     | 1.1L           | 2.3L           |
| Glazing thickness          | 3 mm           | Double 1 mm    |
| Glazing temperature        | 51 °C          | 29.5°C         |

8. Conclusion
This paper addressed the single slope solar water purification system. This technology is promising solution of water treatment of homestead in remote areas. Vapor compression heat pump was used as backup system so that the purifier was able to produce purified water in cloudy and/or at night, while the conventional purifier stop producing in the same conditions. From the experimentation and the data collected we can conclude the following:

- The heat pump system reducing the time required to heat up the brackish water so that the advanced unit producing purified water much earlier.
- On cloudy days, the heat pump system increased the temperature up to 65°C, enabling distillation while the normal still could not.
- The cooled double glazing cover enabled recovery of heat so that the temperature inside the still kept high so that the distillation rate is higher.
- The advanced still produced more than double what the conventional still could produce.

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