Uncovering the feasibility of a double-glazed solar still

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Introduction

Water poverty in rural regions has been a long-term problem for decision-makers throughout the 21st century. Researchers have been addressing this by using different sustainable water treatment techniques divided into evaporation-condensation, filtration, and crystallisation techniques [1]. The most common water treatment processes used are: Reverse Osmosis (62%), Multi-Effect Distillation (14%), and Multi-Stage Flash Desalination (10%) [2]. Yet these active processes require energy inputs, resulting in a large carbon footprint per litre of freshwater production. Thus, there has been an on-going global push to design a cost-effective, passive process driven by solar energy.

Solar still designs (which utilise passive evaporation-condensation) have been the focus of many research efforts to increase efficiency and freshwater yield. Some recent innovations include: thermoelectric cooling systems, vacuum-enhanced chambers, external condensers, ultrasonic foggers, etc. [3]. However, these designs require active energy inputs using pumps and electricity, which increases the operating cost of the solar still and makes it challenging to deploy in rural regions. Another pathway in the literature is directed towards improving the evaporation process inside the solar still by incorporating a multi-stage and multi-effect process, using wick materials to improve the evaporation rate via extended surfaces, porous media, and reflectors [3, 4]. However, limited research has been conducted on increasing the condensation rates in the solar still.

This study investigates the usage of a double-glazed glass cover with running cold water between the two glass layers to cool the condenser surface and (therefore) increase the condensation performance of the solar still. An experimentally validated numerical model is generated to optimise the design and investigate the cost benefits of the proposed design compared to single glass cover conventional solar stills in four different locations (with very different weather patterns) of (1) Sydney, Australia, (2) Martinique, Fort-de-France, (3) Bangkok, Thailand, and (4) Mombassa, Kenya.

Methods

A solar still operates via the simultaneous processes of evaporation and condensation, where solar radiation passes through the glass cover on top of the solar still and is absorbed by the dark basin at the solar still bed, as shown in Figure 1. The salty water in the basin absorbs this heat, driving the evaporation process. The water vapour reaches the cooler glass cover (i.e., the condensation surface), where it condenses into water droplets and slides down to the collection channel at the bottom of the cover. As noted above, in the proposed design, cold water runs within the gap of the double-glazed glass cover to cool the cover and increase the condensation rate.

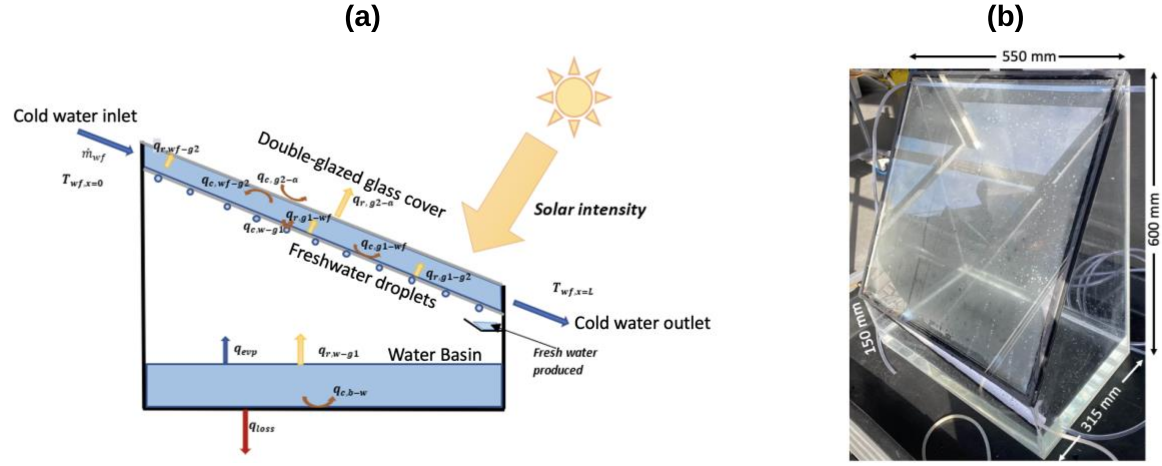

Figure 1: (a) Solar still schematic with double-glazed glass cover; (b) Fabricated solar still

An in-house transient model was developed by coupling System Advisor Model (SAM) and MATLAB, which was adopted from the work published by one of the coauthors [5]. The meteorological data was defined from SAM's built-in library, while the MATLAB program models each control volume by solving the energy, mass balances, and heat transfer rates (i.e., the energy governing equations are presented in Table 1) to calculate the exit temperatures and the evaporation and condensation rates. A uniform grid domain with an iterative procedure was used, where the calculated temperatures and mass flowrates have a minimal residual error compared to the initial assumed values at each control volume (i.e., the error tolerance used is 1E^{-6}). These calculations were simulated at each time step to provide a transient analysis.

Table 1: Governing equations at each control volume

Basin	$m_b c_{p_b} \frac{dT_b}{dt} = I(t)A_b - q_{c,b-w} - q_{loss}$	**Eq. 1**
Water in basin	$m_w c_{P_w} \frac{dT_w}{dt} = I(t)A_w + q_{c,b-w} + q_{wf} - q_{r,w-g1} - q_{c,w-g1} - q_{evp} + \dot{m}_e\left(C_{p,w}T_{wf,x=L} - C_{p,v}T_w\right)$	**Eq. 2**
Lower glass cover	$m_g c_{P_g} \frac{dT_{g1}}{dt} = I(t)A_{g1} + q_{r,w-g1} + q_{c,w-g1} + q_{evp} - q_{c,g1-wf} - q_{r,g1-g2} - \dot{m}_e(C_{p,w}T_{g1} - C_{p,v}T_w)$	**Eq. 3**
Upper glass cover	$m_g c_{P_G} \frac{dT_{g2}}{dt} = I(t)A_{g2} + q_{c,wf-g2} + q_{r,g1-g2} - q_{r,g2-a} - q_{c,g2-a}$	**Eq. 4**
Water film	$\dot{m}_{wf} c_{P_{wf}} \frac{dT_{wf}}{dx} dx = q_{c,g1-wf} - q_{c,wf-g2}$	**Eq. 5**

The following assumptions were made: (1) the solar still is vapor leak proof, (2) constant water depth in the basin, (3) the rate of evaporation is the same as the condensation rate, (4) the flow inside the double glazed glass cover is considered incompressible, (5) the temperature is uniform along the water basin and glass cover, and (6) the salinity in the water basin has a uniform distribution.

The key performance indicators used in this study are the permeate flux produced (calculated per square meter of solar still) and the cost of water. In addition, the proposed solar still was compared to a conventional solar still to represent whether the additional cost of the double-glazed cover is worth the additional cooling on the cover and the additional water produced by the solar still.

Results

This mode was validated through (1) a comparison of published experimental data on solar stills and (2) experimental temperature measurements throughout the day. Figure 2 compares the cumulative water produced, and the basin and water temperature from the numerical model and the literature [6], showing a good agreement.

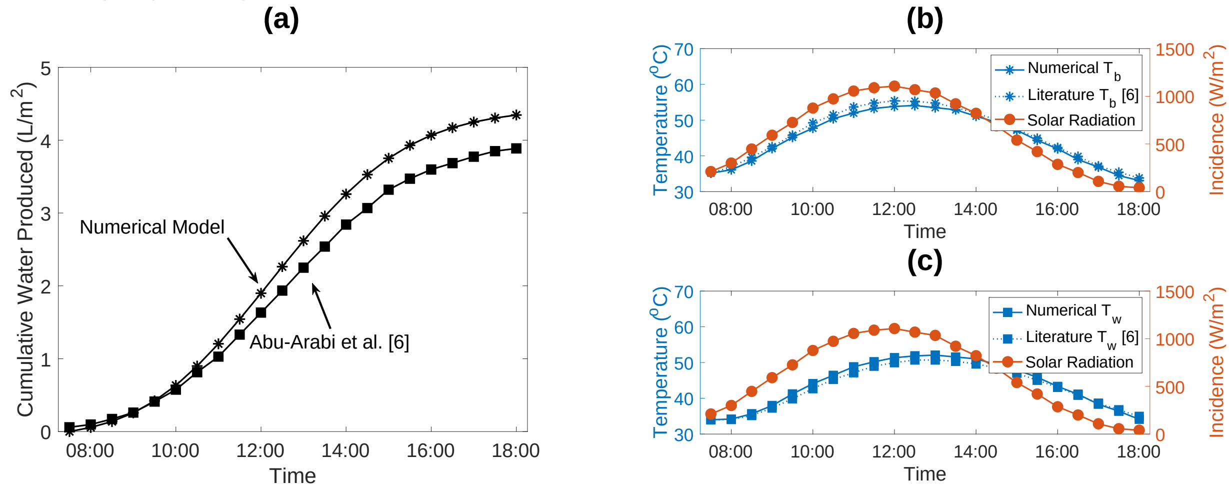

Figure 2: Literature vs. numerical results: (a) Cumulative water produced; (b) Basin temperature; (c) Water temperature

Figure 3 (a) shows the daily production rate as the double-glazed cover gap varies between 5 mm and 20 mm, and the cold-water flowrate increases from 0.1 L/s to 2 L/s. It is shown that there is a maximum daily production between a flowrate of 0.3-0.4 L/s across all the different gap distances. In addition, the maximum daily production (i.e., ~2.985 $\mathrm{L/m^2}$) is at the largest gap distance of 20 mm. This could be explained by having more cold-water medium inside the glass cover, effectively condensing the water vapor at the cover surface. However, one must mention that optimizing both variables (i.e., double-glazed gap and the cold-water flowrate) is shown to be insignificant as the daily production only varies by less than 2% between 2.92 $\mathrm{L/m^2}$ and 2.985 $\mathrm{L/m^2}$.

Figure 3 (b) shows a significant difference in the daily production when applying insulation material to the bottom of the basin. Generally, the larger the insulation thickness and the lower the conductivity would provide higher the insulation properties, reducing heat losses. However, Figure 3 (b) shows that investing in a better-quality insulation material with a conductivity lower than 0.1 $\mathrm{W/mK}$ is more critical than using thicker insulation material.

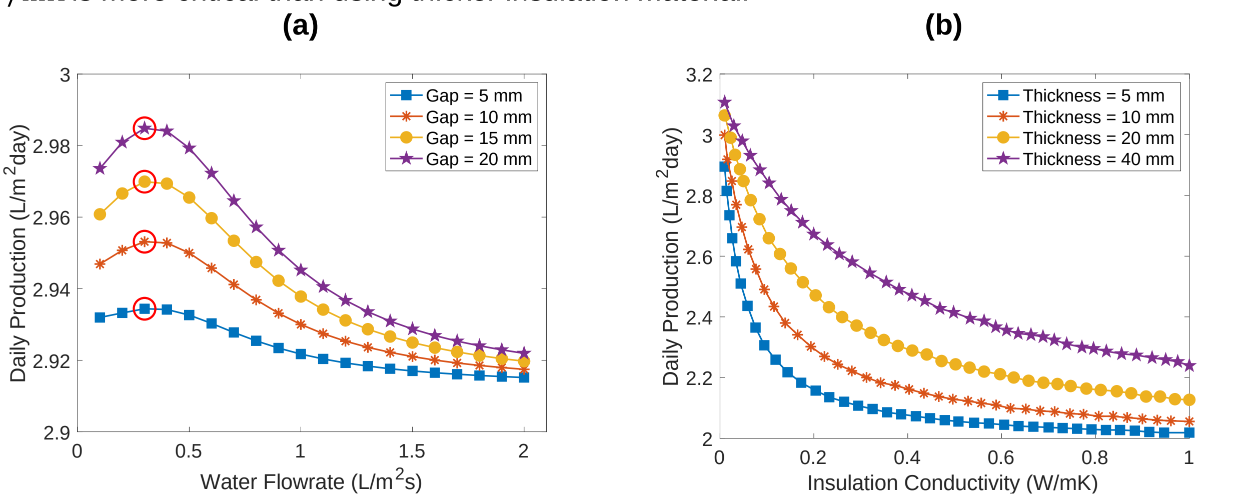

Figure 3: Daily production rate at different (a) water flowrate and gap clearance of the double-glazed cover and (b) insulation conductivity and thickness

In addition to a parametric study, the double-glazed solar still (DGSS) was numerically compared with a conventional solar still (CSS) (i.e., with a single-glazed glass cover) at four different locations: (1) Sydney in Australia, (2) Martinique in Fort-de-France, (3) Bangkok in Thailand, and (4) Mombassa, Kenya. Figure 4 (a) and (b) show that although the DGSS has a higher average daily production than the CSS, the cost of water is lower for the CSS for all locations. This is due to the high cost of the double-glazed cover compared to the single-glazed cover (i.e., even though double-glazed windows are mass-produced, they are 30% more expensive per m^2 than a single-glazed cover). In addition, it is shown that the higher solar radiation in Fort-de-France results in the highest average daily production of water and the lowest cost of water compared to all the other locations. In contrast, Sydney has one of the lowest daily production and highest cost of water values, although it has the lowest average annual ambient temperature relative to the other locations, which improves condensation. Therefore, the double-glazed solar still design is suitable for locations with higher solar radiation than locations with lower average annual ambient temperature.

(a) **(b)**

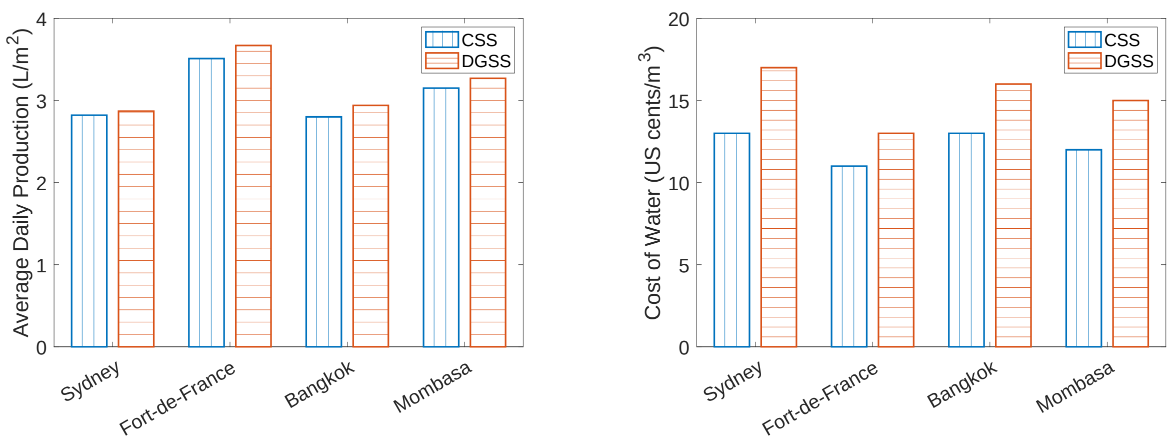

Figure 4: CSS and DGSS (a) Average daily production and (b) cost of water

Overall, the cover modification leads to a slight improvement in the solar still's production rate as it improves the condensation rate. Nevertheless, design optimization is required to decrease the DGSS's cost of water to make it competitive with a conventional solar still.

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