An innovative Cost-effective floating solar still with integrated condensation coils

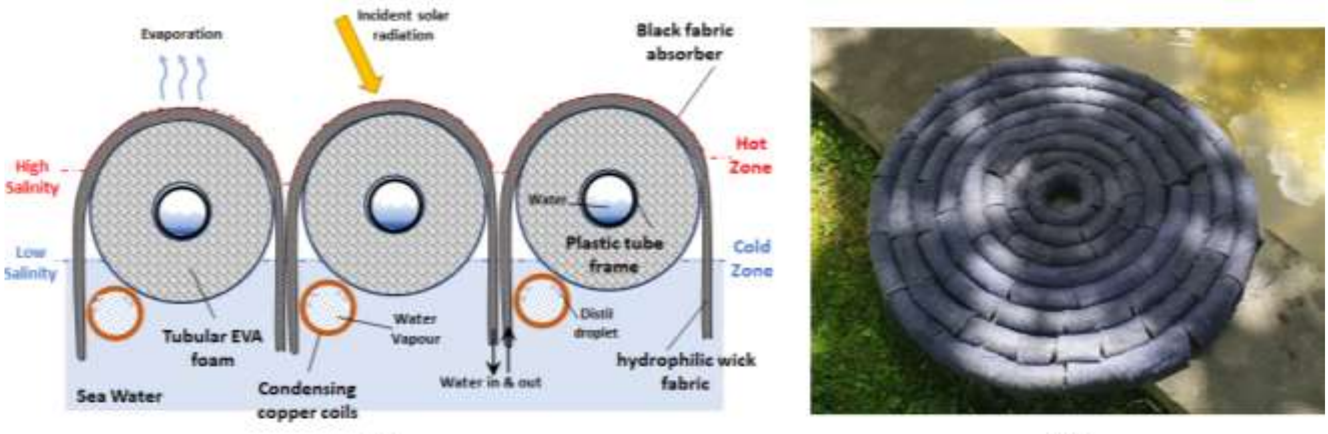
Milad Mohsenzadeh[1], Lu Aye[1] and Philip Christopher[1]

[1] Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Vic 3010, Australia

The shortage in freshwater resources is rapidly becoming a global concern as demand increases [1,2]. Millions of lives are already affected particularly in remote areas with small communities who cannot afford commercial desalination systems [3]. Commercial technologies such as Reverse Osmosis (RO) and Multi-Stage Flash (MSF), which constitute 44% and 42% of globally water desalination capacity by 2019 [4], are often energy-intensive, large-scale, and require significant infrastructure. This makes them financially infeasible for remote areas and highlights the importance of a cost-effective small scale alternative desalination system [5]. Passive solar stills are among appealing yet inefficient systems. The process in these systems is simple. Saltwater is evaporated by heat generated with solar radiation inside a box with a transparent cover. Then the water vapour is subsequently condensed on the inside surface of the cover and collected as drinking water [6]. This technique has a long history, and many studies have been conducted on its design, efficiency, reliability, and cost considerations, but still needs better improvements.

Recently, using the solar heat localisation technique for interfacial evaporation has shown to be a promising approach to improve the performance of thermal desalination systems such as solar stills. The solar heat, in this concept, is localised on the interface of the basin with air, heating only a small quantity of water soaked by a floating porous media instead of a large quantity of bulk water in the basin (as in conventional solar stills) [7,8]. Past studies have used porous carbon-based foam to make the structure with a top coating layer to improve solar heat absorption [9-11]. The porous material also acts as a thermal insulation layer to reduce transfer of heat from interface to the bulk water beneath. Studies implementing solar heat localisation concept for interfacial evaporation have achieved high efficiencies [12-16]; however, further examinations are required to be a fully developed technique. These systems normally have a simple floating structure as a basin, made of low-cost materials which can be deployed on the surface of water without need for costly structure installations [17].

In this research, an innovative floating solar still adopting localised interfacial solar heating for improved evaporation is introduced and experimentally investigated. The developed cost-effective solar still can be deployed on the surface of the sea. This system works under a low vacuum condition inside the evaporation chamber, consists of a hemispherical transparent cover and submerged condensation coils integrated with the basin structure. The basin is designed to utilise a tubular structure made of multi layers of porous foam and hydrophilic cellulose fabric which creates capillary water circulation to clean the basin interface from accumulated salt residuals (Figure 1). A simple mechanism was used in the basin structure to adjust the buoyancy level of the basin in order to control the balance between evaporation rate on the interface and the wetness of the interface. Figure 2 shows the schematic of the developed Floating Hemispherical Solar-driven Desalination (FHSD) system. The extensive area of the transparent cover allows solar radiation to reach the basin from all directions. The submerged copper coils enable the system with enhanced condensation surface naturally cooled by the saline water reservoir while the system is floating.



(a) (b)

Figure 1. Schematic and photo of the floating multi-layer basin structure

The majority of the water vapour generated in the evaporation chamber is discharged into the submerged coils using a solar-powered low-capacity air vacuum through a PVC perforated column at the centre of the evaporation chamber to be condensed on the inner surface of the copper coils. The discharged air is then returned to the chamber via slots around the hemispherical cover right above the basin creating a gust over the basin surface. This mechanism prepares a local low vacuum condition above the basin surface enhancing the evaporation rate.

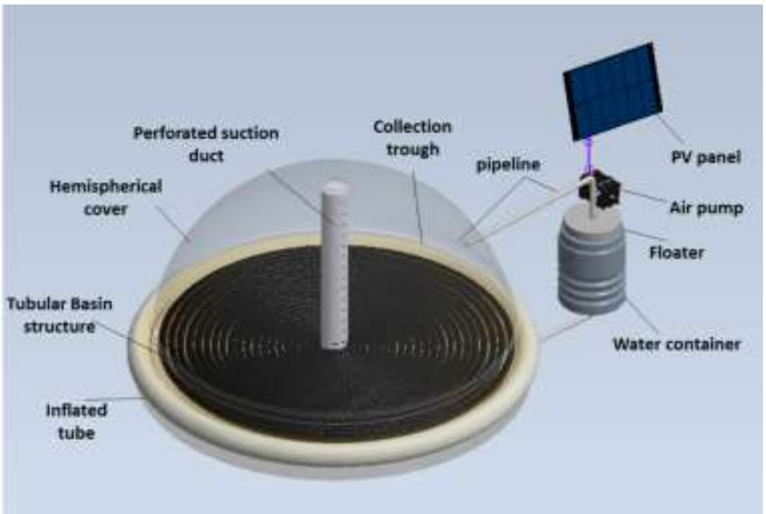
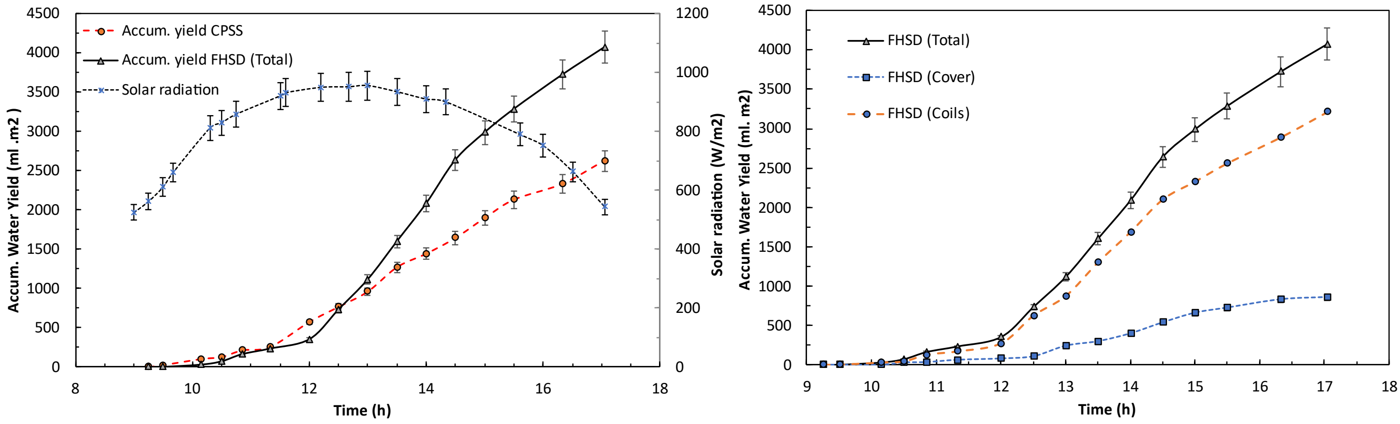


Figure 2. Schematic of the floating hemispherical Solar Still.

The performance of the developed FHSD is examined and compared with a conventional passive solar still (CPSS). Figure 3 provides the accumulated distilled water for FHSD and the CPSS tested together during a summer in Melbourne, Australia. The hemispherical cover on top of the solar still provided a sizable surface for water vapour condensation which was found to collect 23% of the total condensed water (Figure 3(b)); however, most of the water vapour was condensed inside copper coils. The system is capable of generating distilled water at a daily rate of 4.1 L m^{-2} day^{-1} with the distillation efficiency of 34 %. This was 63% higher than the water yield of the reference CPSS tested in the current work (shown in Figure 4).



(a) (b)

Figure 3. (a) Accumulated water yield for FHSD and CPSS setups; (b) Devisions of accumulated water yield distilled on the cover and the coils of FHSD.

The maintenance cost of the developed FHSD is likely to be lower compared to conventional passive solar stills. This is because of capillary water supply into the basin without a pump and self-cleaning of the basin which leads to less periodic cleaning. According to the life cycle cost analysis [18] provided in Table I, it is predicted that the life cycle cost per litre of water (LCCW) generated by the FHSD to be 5.7 ¢ L^{-1}. The estimated LCCW for CPSS built with the total cost of US$289 for the experiments is 9.4 ¢ L^{-1}. The unit water cost of FHSD shows 40 % reduction compared to the CPSS. This is also lower than that of similar solar stills reported in the literature.

Table I. The unit water cost analysis breakdowns (in USD) for Floating Hemispherical Desalination Still (FHSD) and CPSS setups.

Parameter	CPSS	FHSD
Operation life, y	10	8
Interest rate, %	4.0	4.0
Capital cost, $	289	263
Net Aperture area for solar, m^2	0.48	0.35
Salvage value, $	27	64
Capital recovery factor	0.12	0.15
Sinking-fund factor	0.08	0.11
Annual Salvage Value, $	2.25	6.95
First annual cost, $	35.6	39.1
Annual maintenance cost, $	5.34	1.95
Annual cost, $	38.7	34.1
Average daily water yield, L	1.11	1.43
Life cycle cost per litre of water, ¢ L^{-1}	9.4	5.7

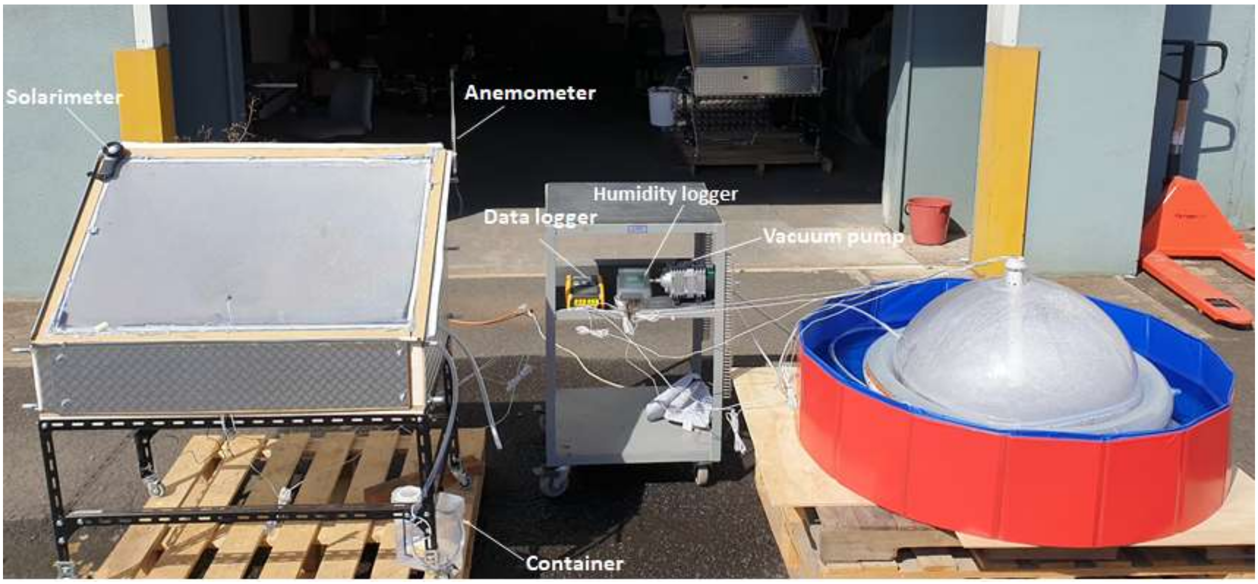


Figure 4. Photograph of the outdoor experiments of FHSD next to CPSS.

The significant advantages of the new system, comparison with other studies, existing shortcomings, and the future considerations were further discussed in this work. The innovative floating hemispherical solar-driven desalination system developed in this work is a feasible alternative to address the water security challenge for water-stressed communities at remote areas or disaster-stricken areas with no access to an energy infrastructure.

References

1. S. Hoffman, 2009, '*Planet water: investing in the world's most valuable resource'*, John Wiley & Sons.
2. Hasan, Emad, et al., 2019, 'Asessment of physical water scarcity in Africa using GRACE and TRMM satellite data', *Remote Sensing,* 11.8, p904.
3. Gude, Veera Gnaneswar, 2017, 'Desalination and water reuse to address global water scarcity', *Reviews in Environmental Science and Bio/Technology,* 16.4, p591-609.
4. Intelligence, Global Water, 2019, "*The IDA Water Security Handbook 2018–2019*." Media Analytics Ltd.: Oxford, UK.
5. Shiklomanov, Igor A., and John C. Rodda, eds, 2004, 'World water resources at the beginning of the twenty-first century', *Cambridge University Press*.
6. Prakash, Om. 2019, '*Solar Desalination Technology',* Springer Nature Singapore Pte Ltd.
7. Sharshir, Swellam W., et al., 2020, 'New hydrogel materials for improving solar water evaporation, desalination and wastewater treatment: A review', *Desalination,* 491, p114564.
8. Li, Zhengtong, et al., 2019, 'Arched bamboo charcoal as interfacial solar steam generation integrative device with enhanced water purification capacity', *Advanced Sustainable Systems,* 3.4, p1800144.
9. G. Ni, S.H. Zandavi, S.M. Javid, S.V. Boriskina, T.A. Cooper, G. Chen, 2018, 'A salt-rejecting floating solar still for low-cost desalination', *Energy Environ. Sci.*, 11 (6), p1510–1519.
10. Kim, Kwanghyun, et al., 2019, 'Three-dimensional solar steam generation device with additional non-photothermal evaporation', *Desalination,* 469, p114091.
11. Ghasemi, Hadi, et al., 2014, 'Solar steam generation by heat localization', *Nature communications,* 5.1, p1-7.

12. Zhang, Lenan, et al., 2020, ’Modeling and performance analysis of high-efficiency thermally-localized multistage solar stills’, *Applied Energy,* 266,11, p4864.
13. J. Xu, Z. Wang, C. Chang, B. Fu, P. Tao, C. Song, et al., 2020, ’Solar-driven interfacial desalination for simultaneous freshwater and salt generation’, *Desalination,* 484, p114423.
14. Tao, Peng, et al.,2018, ’Solar-driven interfacial evaporation, *Nature energy*, 3.12 , p1031-1041.
15. Xu, Jiale, et al., 2020, ’Solar-driven interfacial desalination for simultaneous freshwater and salt generation’, *Desalination*, 484 , p114423.
16. Nafey, A. Safwat, et al., 2002, ’Enhancement of solar still productivity using floating perforated black plate’, *Energy Conversion and Management*, 43.7, p937-946.
17. G. Liu, T. Chen, J. Xu, G. Yao, J. Xie, Y. Chen, et al., 2021, ’Salt-rejecting solar interfacial evaporation’, *Cell. Rep. Phys. Sci*., 2.1, p100310.
18. Fath, Hassan ES, et al., 2003, ’Thermal-economic analysis and comparison between pyramid-shaped and single-slope solar still configurations’, *Desalination,* 159.1, p69-79.