Solar energy technologies for passive and low-cost water desalination

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Department of Energy - Politecnico di Torino. April 29, 2019

**Abstract**

Global warming and clean water scarcity are progressively impacting economies and societies. International collaborative efforts have taken place to limit global temperature rise and address clean water scarcity in the most water-stressed areas, where nearly two-thirds of global population will live by the year 2025. Inadequate water supply, sanitation and hygiene are mostly emphasized in remote and developing countries as Sub-Saharan Africa, Central Asia, Southern Asia, Eastern Asia and South-Eastern Asia which present bad economic conditions and poor infrastructure, but also one of the most abundant and permanent energy resource: solar energy. In this context, a frugal approach to innovation may offer a more sustainable, flexible (i.e. accessible to more people), robust and stand-alone technologies covering fundamental needs of water. However, current solar passive technologies (where no moving parts are present) although interesting have unsatisfactory performance when operated with an energy flux lower than 1 kW $m^{-2}$ (namely one sun) and great effort is still required from the scientific community. Thus, the focus of this research is to propose promising and innovative technologies able to passively produce clean water exploiting renewable energy sources like solar energy.

First, the attention is focused on increasing solar light harvesting. Ghasemi and co-workers demonstrated, with their seminal work *Solar steam generation by heat localization* published in 2014 in Nature Communications, that solar steam generation is enhanced by the concurrent action of three phenomena: (i) heat confinement in the evaporative region; (ii) capillary action to continuously supply water to the narrow evaporative region and (iii) effective thermal insulation. However, this successful strategy was enabled by advanced materials (exfoliated graphite and carbon foam). Since then, a number of works have followed and many new materials for solar steam generation have been suggested. In this thesis, an efficient solar steam generator powered by solar energy is presented and studied. This work demonstrated that the above conditions can be safely ensured relying upon a smart combination of common and inexpensive materials without resorting advanced nano-structured materials.

Both simulations and experiments have proved the good performance of the proposed device.

Once the solar light harvesting process is optimized, it is important to improve the use of the harvested energy flux. In fact, despite the large solar-to-vapor conversion efficiency demonstrated with the considered steam generator (as well as in the several studies from the literature), the productivity of clean water is still far from that obtained in large-scale conventional desalination plants. The main reason is that, as commonly done in large desalination thermal plants, the latent heat of vaporization should be recovered and re-used several times before being rejected into the environment. Therefore, multiple evaporation/condensation processes are necessary in order to implement an efficient energy management through which a significant enhancement in freshwater yield can be achieved at a fixed solar input.

Thus, a step forward consisted in including an efficient condensation process with multiple re-uses of the heat of condensation. A passive multistage and low-cost solar device able to produce freshwater from seawater is conceived, prototyped and widely tested under both laboratory and outdoor conditions. Under realistic conditions, a distillate flow rate of almost 3 L $m^{-2}$ $h^{-1}$ from seawater at less than one sun (namely twice the yield of recent passive complete distillation systems) is demonstrated. Theoretical models also suggested that the concept has the potential to further doubling the observed distillate rate.

Once the effectiveness of the described multistage prototype is established, we wondered how to improve it further by hybridizing it with other successful and innovative solutions documented in the literature. Therefore, this thesis reports also the results of the research activity developed in collaboration with Prof. Chen's group at MIT. In detail, the promising passive desalination technology is further investigated and improved prototyping a new version of the passive distiller. The system represents a synergy between the device developed at MIT and characterized by a smart design to minimize salt accumulation, and the modular device developed at Politecnico di Torino and characterized by enhanced yield. Summing up, it presents three main improvements with respect to the original distiller which currently, to the best of my knowledge, has the world record in terms of distillate productivity among all the solar passive desalination technologies (based on complete distillation): i) increased productivity, ii) lower cost and iii) passive and efficient salt rejection.

Summing up, this work is motivated by the necessity of providing affordable and accessible fresh water during emergency conditions. It mainly proposes a stand-alone, rapidly deployable and efficient desalination system. Parallel to this, the effectiveness of the salt rejection mechanism may ensure long-term stability of performances. Then, up-scaled versions of this technology (with no additional environmental impact) are envisioned to operate permanently in both coastal and non-coastal areas due to the ability of treating different feed water types.