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Performance investigation of atmospheric water harvesting systems

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ABSTRACT

In this paper performance and limitations of commercially-available atmospheric water harvesting (AWH) systems are experimentally investigated. A new experimental setup and test procedure, following the relevant ASHRAE and ANSI/AHRI standards, are developed to measure the water harvesting rate and input electrical power of several residential-size AWHs from different manufacturers. The setup is equipped with an environmental chamber to mimic all climatic conditions in research laboratory at Simon Fraser University and to obtain performance characteristics of AWH systems. The results show the range of water harvesting rate, energy intensity ranging from 1.02 kWh/L for warm and humid to 6.23 kWh/L for cold and humid climates, and climatic limitations of the conventional AWH technology that can be used as a platform for further development of higher efficiency AWH systems in future.

1. Introduction

Over the 20th century and into the 21st century, the global population has increased by 300%, while water consumption has increased by 600% [1,2]. Freshwater is becoming a scarce commodity as climate change, man-made pollutants entering the water system, and over-withdrawal of existing aquifers place enormous strain on freshwater supplies. The distribution of freshwater around the globe is highly uneven, leading to regional shortages or excesses of water resources. The most commonly used index to determine magnitude of regional water resources is the Falkenmark Stress Indicator (FSI), which classifies a country in different categories of water shortage based on per capita liquid water resource availability (PWR) [3]. Based on this index, the United Nations has predicted that 48 countries will experience water stress or scarcity by 2025 [3]. Four billion people in the world face at least one month of water scarcity every year [4]. The water crisis has or will soon turn into food crisis in many areas of the world. To avert the looming water-food crisis, certain measures should be adopted, including, but not limited to: i) water conservation, ii) reducing pollutants entering the water system, iii) upgrading current infrastructure, and iv) improving fresh water generation technologies.

With an estimated 12,800 trillion liters of renewable water available in the atmosphere, atmospheric water harvesting (generation) has the potential to be a viable solution to address some of the global needs for freshwater, especially in locations where even saline and/or brackish water is not available [5]. Combining these facts and considering the challenges and shortcomings of existing centralized water provision and delivery systems, the idea of decentralized atmospheric water harvesting (AWH) systems has emerged and followed by a number of researchers and manufacturers during the last few decades. A conventional AWH operates using vapor compression refrigeration (VCR) unit to condensate water from ambient air by cooling it below its dew point temperature.

There is a number of claims on the performance and capabilities of the commercially available AWH. However, the literature

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lacks a critical and independent investigation into realistic performance, functionality, and limitations of such AWH systems. This study aims to provide a systematic investigation on the performance of a few commercially available AWH systems under various climatic conditions.

2. Literature review

Decentralized atmospheric water harvesting is a solution to a variety of challenges in common water purification processes. If the input power is supplied from clean energy sources (e.g. solar, wind, tidal, geothermal), AWH will be a renewable and sustainable water resource since: i) atmospheric humidity is renewed naturally through evaporation from the ocean, and ii) AWH process does not generate any side effect or by-products harmful to the environment.

There are several studies in the literature focusing on the process and functionality of AWH systems for water harvesting [6–9]. However, most of these studies have praised the viability of the process, especially near tropical and coastal areas where temperature and humidity levels are typically high [10–13]. One of the first works dealing with water harvesting from atmosphere was published in 1947 [14]. An apparatus was invented that consisted of a system of vertical and inclined channels underground to collect water from atmosphere by cooling moist air to a temperature below its dew point. Gad et al. [15] reported water harvesting using a liquid desiccant via absorption as well as using a solid desiccant via adsorption–desorption processes. Milani et al. [12,16] classified moist air dehumidification methods into three main categories: i) condensation on cooling surfaces, ii) sorption using desiccant materials, and iii) gas separation using membranes. They modeled, built, and tested a solar-assisted sorption dehumidifier that was added to an air-cooled heat exchanger to dehumidify air for reducing the energy consumption of an air conditioning system. It was shown that their system could be used for AWH to deliver 5.2 liters of water per day in Sydney, Australia.

Scrivani and Bardi [6] calculated the energy consumption of AWH by considering typical efficiency for major components in these systems and reported the results for several weather scenarios in three Mediterranean countries: Jordan, Lebanon, and Morocco. They discussed the possibility of using solar power to run absorption chillers as the source of cooling for water condensation. Based on their calculations, the energy consumption per unit of water generation varies between 2256.54 $\mathrm{kWh/m^3}$ for Tripoli to 7910.04 $\mathrm{kWh/m^3}$ for Rayack, both in Lebanon. Habeebullah [7] calculated the water yield of an AWH in relatively hot and humid climate of Jeddah, Saudi Arabia, using a developed mathematical model. Based on the reported data, the monthly estimated average water yield per unit area of dehumidifier (evaporator) coil during August and February were 509 and 401 $\mathrm{kg/m^2}$, respectively.

Gido et al. [17] introduced a new index, moisture harvesting index (MHI) as the ratio of latent heat of condensation to total heat transfer at the dehumidifier, for evaluating the functionality and cost-effectiveness of AWH. They estimated the MHI for several cities around the world and determined Cabanatuan in Philippines with average MHI of 0.59 as the most suitable location for AWH among the considered locations. They also concluded that $\mathrm{MHI} < 0.3$ represented unfavorable conditions for AWH.

Lekouch et al. [18] focused on natural dew and fog collection from atmosphere in an arid region of southwest Morocco. The dew water was collected using standard passive dew condensers and fog water was collected utilizing planar fog collectors. They also simulated the dew yield and reported potentials of 0.3–18.1 liter per $\mathrm{m^2}$ of collection surface from May to October (in total) for 15 Moroccan cities.

Sharan et al. [8] also studied dew yield from conventional, uninsulated, corrugated galvanized iron in northwest rural India. They estimated that for common large roofs 100–300 $\mathrm{m^2}$ in northwest India region, dew water could provide 600–1800 L during the dry season (late September to early May) when needed most by the population.

Bergmair et al. [9] analyzed a membrane facilitated AWH using a mathematical model. They showed that in warm and humid areas, using a selective membrane to concentrate the water vapor before cooling and condensation would significantly decrease the energy consumption of AWH systems. Based on their obtained indexes, between 40% and 68% saving in energy consumption per unit volume of water harvested would be achieved.

Our comprehensive literature review indicates that realistic performance evaluation of AWH has not been studied independently, and the pertinent literature lacks the followings:

- Performance of commercially available AWH in different climates,
- A standard and/or procedure for performance evaluation of AWH,
- A general and in-depth understanding of functionality and limitations of AWH technology.

The present study aims to develop a systematic experimental procedure for evaluating the performance of AWH systems. We tested a few commercially available residential-size AWH in our lab under a variety of climatic conditions using environmental chambers. The results were analyzed to establish realistic functionality, performance, and limitations of the tested AWH systems.

3. Experimental setup

A test-bed is custom-built to study the effects of climatic conditions on water harvesting rate and performance of commercially available AWH systems. The test-bed is equipped with a large environmental chamber (Espec, model EPX-4H Platinous) to provide the inlet air stream with a wide range of desired temperature (T) and relative humidity (RH) to mimic targeted ambient conditions. A schematic and a few pictures of the test-bed are shown in Figs. 1 and 2. The test-bed is equipped with several Rotronic temperature and humidity sensors (model HC2-S3 with accuracy of ± 0.1 °C and ± 0.5% RH), air flow measurement (TSI anemometer vane model 5725) with accuracy of ± 1.0%, and Fluke 902 clamp meter with accuracy of 2.0% for input electric power measurements.