Solar HDH desalination for coastal hotels: literature review and research trend

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Abstract. Water is essential for the hotel industry, its disposition is key to ensure the viability of the tourism sector that grows disproportionately day by day plus the scarcity of water in the world, this situation forces hotels to find alternatives to meet the demand for water. One of the preferred alternatives is solar water desalination. The purpose of this paper is to demonstrate through this first literature review whether solar desalination is a viable technique to meet the demand of potable water in a medium-sized hotel in a coastal area. We conducted a review of the literature published between 1987 and 2018, the subject of which is solar HDH desalination. Inclusion and exclusion criteria were formulated and applied to determine the most relevant studies to achieve the purpose of this research. The review found that solar desalination can be feasible to apply in hotels if they have large amounts of land for installation or the demand for water is not large. However, there are more economic methods to desalinate water while at the same time producing more water with similar sizes of facilities. Such results have practical implication for the use of the systems of hotels in general.

Introduction

Over the past 50 years, global water consumption has increased significantly\cite{1}. The hotel industry is not immune to this situation, especially since it ranks as the largest industry in terms of international trade, and continues to grow day by day\cite{2}. Consequently, due to the increasing demand of water in this industry, solar desalination seems to be the most suitable solution to solve this problem in coastal areas because this areas have abundant seawater and sunlight\cite{3}. One of the most preferred method for small scale application in remote areas is solar desalination by the humidification and dehumidification (HDH), because the cost of fabrication, operation and maintenance are lower than other desalination techniques\cite{4-5}. Several researches have been conducted to research the solar desalination HDH, some of such literature will be illustrated in the following paragraph.

Firstly, in 1998 Farad and Al-Hallaj built an HDH desalination unit in Iraq. This unit collected 12 L/d per m\textsuperscript{2} from a single solar collector, which meant an improvement compared to previous research, showing only a single solar basis under the same conditions\cite{6}. It is worth mentioning Ben Bacha et al, they presented a comprehensive research models, simulations and experimental validation of HDH systems, which aid the development of future improvements in the system \cite{7}.

In addition, Joo and Kwak built a multi-effect small-scale optimized unit, they concluded that the average performance of the unit was 2.0 \cite{8}. Another significant improvement can be found in Riffat and Mayere paper, in their research, they used a V-shaped hub, increasing the thermal efficiency to 38\%, when the water temperature reached 100 °C at the output of this hub.
Hence, they concluded that the V shaped concentrator is a promising application for solar desalination [9]. In the research of Houcine et al., it was used a pilot plant with five stages and a total collector area of 127 m², it was achieved an output of 4L/m² daily [10].

A restraint in the production was found in Kheder work made, in which they concluded by a techno-economic investigation, that HDH has potential only for plants that are below 10 cubic meter per day [11]. Also important was the research of Nafey shows a production of 9L/m² daily [3], while Muller-Holst’s resulted in 13L/m² a day [12].

Although there is literature about HDH solar desalination, no papers were found regarding its application in the hotel industry to supply water consumption. Therefore, we sought to answer the following research question: whether the HDH system may be feasible in the production of fresh water to meet the demand for water in hotels? Our study makes a comprehensive review of the current experimental literature, and state of the art of the HDH system. Seeking to respond to such research question, focused on the following two objectives: (1) to verify if the application of HDH technology is viable for hotels in coastal areas; and (2) to determine if the size requirements for such technology does not exceed 50 m², taking to account the state of the art of the system. Thus, the structure of this paper is as follows: In Section 2, the frame of reference and propositions are presented. In Section 3, the methodology is detailed. Then, in Section 4 analysis are made and the results are discussed. Finally, Section 5 presents the conclusions of the research.

Related Work

There are many technologies to desalinate water, such as reverse osmosis, multi effect distillation and multi flash stage desalination [13]. Among them, the HDH technology is a system based on the air’s characteristics, by being able to charge a greater quantity of water when raising its temperature. In the HDH system, the air is brought into contact with salt water (previously heated in the solar heater) inside the humidifier, where it obtains latent heat and water vapor. This air is then put in contact with a cooling surface (cooled by medium of the salt water that is subsequently heated) in the dehumidifier; the result of the condensation is the fresh water that is then stored in a tank [1]. Its basic system consists of packed towers, energy absorber, pumps, fans and heat exchangers [2]. However, there are several improvements and variations to the basic system [2, 4].

The humidification dehumidification process works as moisture content of air increases progressively with elevated temperature [38]. The simplest form of the HDH process Fig. 1 consists of three subsystems: (a) air and/or water heater, which can use various sources of heat, such as solar, thermal, or combinations of these; (b) humidifier or evaporator; and (c) dehumidifier or condenser [24,28,32].

Further, HDH systems are classified under three main broad categories[34]: (1) type of circulation; (2) type of heating; and (3) type of circulation loop.

![Fig.1. Schematic diagram of HDH system](image-url)
A comparison of 12 systems was made, where 8 systems, the simplest form of the HDH process, two of them present a cogeneration, one by hybrid humidification-dehumidification water desalination and air conditioning system and the remaining 4 have HDH systems have been called "multi-effect humidification" (MEH) where the heat can be used many times to produce vapor[40].

In order to establish a framework for the HDH system to be implemented in the hotel industry, it is necessary to delimit it from the wide variety of configurations, plant sizes, and system improvements available in the literature. To do this, we mainly based the framework from three important publications from leading authors in the specialized literature, Shani, Housine et al. and Nafey et al., since they made some of the most thorough investigations and significant improvements on the system in recent years [4,10-11].

Muller-Holst et al.’s [13] research is also key for the application in question, since its improvement does not depend on large sizes to produce more water. Therefore, their research is also used as point of reference to determine the feasibility of the system, considering its size and water production, which is measured in liters per day. It was also a key point of this investigation to determine the water demand found in hotels. The water in the hotels can be used in many ways depending on the hotel or resort, such as irrigation, toilets, showers, laundry, and even swimming pools, among other things [8]. In Hawaii, for example, where the hotel industry is responsible for 30% of the state's income, water consumption can vary between 38,000 and one million liters of water per year [9]. The estimation is that only one room may have a consumption of 300 liters per day for each of these hotels [10].

Going further in the use that can be given to desalinated water, we cite what S. Duranceau explained on page 1 of his work: "desalinated water is considered corrosive because of its inherently low mineral content and may not be suitable for consumption without adequate post-treatment [11]. Hence, human consumption in hotels from such kind of water would imply an additional system to make it suitable for consumption. However, such additional system for potable water are beyond the scope of this paper. Hence, we will stay on focus on the use that can be given to water that is not going to be ingested or does not have direct contact with humans. Due to the corrosive quality of the produced water, it has been decided to not consider its application in laundry, since there may be damage done to the clothes, by untreated water, leaving its uses for toilets and irrigation.

Therefore, considering the framework presented in this section; the following two propositions are made. First, based on the information found about the production of the HDH system, we propose:

Proposition 1: the HDH system meets the water demand of a medium size hotel

Making use of the reference about the different improvements that have been made on this system, which are aimed at obtaining a greater volume of desalinated water, we make the second proposition:

Proposition 2: the HDH system is as economically competitive, as other desalination processes such as reverse osmosis, multi-effect distillation and desalination multi flash stage.

Methodology

The study by Newbert [13] and Sanahuaja [14], was used as a guideline for carrying out this research where seven steps were developed. After defining our research goals and question, we started with the first step, we selected the databases to find the most relevant studies of the subject.

The databases chosen were Scopus, Science direct and EBSCOhost. In the second step, the selection of keywords was made. "HDH", "humidification dehumification", "solar desalination" were chosen to obtain results according to the theme and thus diminish existing biases. In the third step, the time interval was defined. The selected period was from 1987 to 2018 to analyze the advances in technology. The fourth step focused on the inclusion and exclusion criteria, we include only journal articles and conference papers and exclude thesis, books and manuals.

We only include papers that were written in English and remove those in other language. This strategy produced the following number of papers: 95 of Scopus/Science Direct, 10 of EBSCOhost. Then the number of documents to analyze was reduced using the fifth step) including a combination of secondary keywords: water desalination. The result was 56 papers. Thereby, we proceeded to read
the summaries, to reduce redundancies (sixth step) and considering only the relevant documents. Finally, we got 18 papers of science direct/Scopus, 4 of EBSCOhost. To complete it, a manual search of other documents was made using complementary databases: Research Gate and Google Scholar, adding three papers. As a result, 25 relevant articles were admitted carrying out the review. Then to track and manage the found documents, we used Mendeley.

Results, Analysis and Discussion

The results of this review cover a total of 25 articles, Fig. 2 illustrates a summary of the articles reviewed, it shows most of the papers are articles from science direct, Scopus and EBSCOhost.

![Fig. 2. Summary of the results](image)

Table 1 shows the main journals that were involved in this Research, were most journal cited were Desalination (SJR Q1, 1.96), Energy conversion and management (SJR Q1 2.54) and Energy Procedia (SRJ 0.49).

| Journal                                    | Citations | SJR   | H-index |
|--------------------------------------------|-----------|-------|---------|
| Renewable Energy                           | 2         | Q1 1.85 | 143     |
| Renewable and Sustentable Energy Reviews   | 1         | Q1 3.04 | 193     |
| Process Safety and Environment Protection | 1         | Q1 0.80 | 52      |
| Proceedings of the ASME Disign Engineering T. | 1         | NA 0.14 | 41      |
| Procedia Engineering                       | 1         | NA 0.28 | 40      |
| Journal of Environmental Management        | 1         | Q1 1.16 | 131     |
| Journal of Cleaner Production              | 1         | Q1 1.47 | 132     |
| International Journal of Hydrogen Energy   | 1         | Q1 1.12 | 173     |
| Energy Procedia                            | 2         | NA 0.49 | 56      |
| Energy Conversion and Management           | 2         | Q1 2.54 | 147     |
| Energy                                     | 1         | Q1 1.99 | 146     |
| Desalination and Water Treatment           | 1         | Q2 0.40 | 40      |
| Desalination                               | 11        | Q1 1.96 | 139     |

The first proposition pursued by this literature review is to check whether the HDH System can meet the total or partial water demand of a medium size hotel, which according to the research has about 120 rooms [8-9]. Thus, the review showed Table 2 states that this technique is only viable if the hotel's water demand is small or the hotel owns vast amount land to install the plant and increase the production of water.
The HDH system is not competitive toward other desalination technologies. This leads us to assert that the cost of water produced with reverse osmosis (RO) that varies between 0.26 € and 3.14 € per m$^3$ of potable water per day is between € 3.20/€ 9 per m$^3$ of water produced. Multi effect (MED) with cost varying between 0.76 € and 1.50 € per m$^3$ of water produced also is not competitive for capacities less than 70 cubic meters per day.

Table 2. Summary of the productivity of HHD desalination systems

| Authors              | Year | Results                                                                 | Reference |
|----------------------|------|-------------------------------------------------------------------------|-----------|
| Ashtafizadeh and Amidpour | 2012 | The productivity of the unit was found to be 0.0059 [kg/s]              | [24]      |
| El-Agour             | 2010 | The productivity of the unit was found to be 8.22 [kg/d]                | [25]      |
| Wang et al.          | 2012 | The productivity of the unit was found to be 30.873 [kg/m$^2$ d]        | [26]      |
| Hermosillo et al.    | 2012 | The productivity of the unit was found to be 1.45 [L/h]                 | [27]      |
| Farsad and Behzadmehr| 2011 | The productivity of the unit was found to be 27 [kg/h]                  | [28]      |
| Amer et al.          | 2009 | The productivity of the unit was found to be 5.8 [L/h]                  | [29]      |
| Zhani and Ben Bacha  | 2010 | The productivity of the unit was found to be 21.75 [kg/d]               | [30]      |
| Muthusamy et al.     | 2014 | The productivity of the unit was found to be 0.82 [kg/h]                | [31]      |
| Kabeel et al.        | 2014 | The productivity of the unit was found to be 23.6 [kg/h]                | [32]      |
| Yuan and Zhang       | 2007 | The productivity of the unit was found to be 38 [kg/d]                  | [33]      |
| Ghalavand et al.     | 2014 | The productivity of the unit was found to be 151 [kg/d]                 | [34]      |
| Gao et al.           | 2008 | The productivity of the unit was found to be 60 [kg/d]                  | [35]      |
| Nada et al.          | 2015 | The productivity of the unit was found to be 4.74 [kg/h]                | [36]      |
| Kang et al.          | 2014 | The productivity of the unit was found to be 72.6 [kg/h]                | [37]      |
| Chang et al.         | 2014 | The productivity of the unit was found to be 63.6 [kg/h]                | [38]      |
| El-Shazy et al.      | 2012 | The productivity of the unit was found to be in the range from 1.5 to 2.5 [L/h] | [39]      |
| Yamali and Solmus     | 2007 | The productivity of the unit was found to be 4 [L/m$^2$/per day]         | [19]      |
| Muller-Holst et al.  | 1998 | The productivity of the unit was 13 [L/m$^2$/per day]                    | [12]      |
| Semiat               | 2000 | The collecting area surface requires to be around 250 [m$^2$]            | [18]      |
| Cipollina            | 2014 | The productivity of the units was 100 [L/per day]                        | [15]      |
| Houcine et al.       | 2006 | The productivity of the unit was found to be 4 [L/m$^2$/per day]         | [10]      |
| Nafey                | 2004 | The productivity was 9 [kg/s]/L/day                                     | [3]       |

The productivity of this method is among 4 and 13L per square meter of water per day. The second proposition of this review deal on whether the HDH system is as economically competitive as desalination by reverse osmosis, multi-effect distillation and multi stage flash desalination. As before, the review also rejects such proposition. Considering mainly with what Tzen20, Avlonitis [21], Karagiannis [22] and Alkalis [23] in the Table 2, agree that the cost of water production, using solar desalination technology is between € 3.14-€ 9 per m$^3$. This means at least more than three times the cost of other process such as multi stage flash(MSF), whose cost oscillates between 0.42 € -1.01 € per m$^3$, or multi effect (MED) with cost varying between 0.76 € -1.95 € per m$^3$, or the cost of water produced with reverse osmosis (RO) that varies between 0.26 € -0.35 € per m$^3$. This leads us to assert that the HDH system is not competitive toward other desalination technologies.

Table 3. Summary of the cost productivity of HHD desalination systems

| Authors               | Year | Results                                                                 | Reference |
|-----------------------|------|-------------------------------------------------------------------------|-----------|
| Tzen and Morris       | 2003 | The cost of water produced was found to be in the range of 1.50€-5.00 € per [ m$^3$] | [20]      |
| Karagiannis and Soldatos | 2008 | The cost of water produced was found to be in the range of 2.50€-6.30€ per [ m$^3$] | [22]     |
| Avlonitis             | 2002 | The cost of water produced was found to be in the range of 3.20€-8.00€ per [ m$^3$] | [21]     |
| Alkaishi.Mossad       | 2017 | The cost of water production can vary 2.40€ - 6.19€ per [ m$^3$]         | [23]     |

Gorjian also supports that this method should be applied in regions where the demand does not exceed 200 cubic meters per day[17]. The results obtained on the size of the desalination plant emphasize that large amounts of land are required. This coincided with Semiat, this investigation stated that the collecting surface area should be about 250 square meters just to produce 1 cubic meters of potable water per day [18].

Likewise, the results obtained regarding the production of solar desalination plants show that they do not produce quantities greater than 20 L per day. This agrees with what Yamali and Solmus[19], Houcine et al.[10], Nafey [3], Muller-Holst et al. [12] and Farid [6], all agree that the productivity of this method is among 4 and 13L per square meter of water per day.
Conclusions

Based on the results of the investigation the application of the HDH system in hotels exceeding 200 rooms is not recommended. In addition, since there is dependence of the HDH system for big facilities to produce big amounts of water, we conclude that it may not be convenient for most industries and is not currently a convenient solution for obtaining fresh water in communities with a limited space. The production of water could be increased doubling or tripling the size of the installation, but even so, it would not be enough to satisfy the water demand in a significant way, given that the production is linked to the size of the solar collector.

Such limitation may be an opportunity for future research on its application to small hotels (30 rooms). Further, alternative technologies to desalinate may be reviewed in future research. For instance, Reverse Osmosis and MSF (plant requires large dimensions) show some of the lowest production costs among desalination technologies [1, 16].

Finally, since this paper presents in this literature review on HDH solar desalination in hotels in coastal areas. The practical and methodological implications are important, since prior to this paper, Bouroni’s statement of whether the HDH system was useful in hotels [2], was considered true, and now an opportunity to carry out future research in the HDH system innovation and/or its potential application to other markets, or for alternative technologies, is now available.

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