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Desalination of salty water using vacuum spray dryer driven by solar energy

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HIGHLIGHTS

- Theoretical analysis for desalination under reduced pressure aided by solar energy,
- New approach and design for a solar-aided desalination system under reduced pressure,
- New approach and design for solar energy collector using spherical-shaped system,
- Recycled latent heat of evaporation, waste heat from the vacuum pump, heat collected from the solar panels and droplet colour were considered in the theoretical analysis.

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ABSTRACT

This paper addresses evaporation under vacuum condition with the aid from solar energy and the recovered waste heat from the vacuum pump. It is a preliminary attempt to design an innovative solar-based evaporation system under vacuum. The design details, equipment required, theoretical background and work methodology are covered in this article. Theoretically, based on the energy provided by the sun during the day, the production rate of pure water can be around 15 $kg/m^2/day$. Assumptions were made for the worst case scenario where only 30% of the latent heat of evaporation is recycled and the ability of the dark droplet to absorb sun energy is around 50%. Both the waste heat from the pump and the heat collected from the photovoltaic (PV) panels are proposed to raise the temperature of the inlet water to the system to its boiling point at the selected reduced pressure.

1. Introduction

Water and energy are fundamental necessities for life on Earth and to sustain the modern world. In many parts of the world, the control and exploitation of water and energy has driven economic development. In many other places there are shortages in fresh water and energy supplies. Drinking water of acceptable quality has become a scarce commodity not to mention unevenly distributed geographically worldwide [14,24]. The World Health Organization (WHO) has estimated that lack access to drinking water may be an issue for more than a billion people [15]. The vast majority of these people are from undeveloped countries and/or living in rural areas where there is low population density. In remote locations it is very difficult and costly to install conventional clean water solutions, [25]. In many countries where there are shortages of clean and fresh water, there are many other water resources that have potential to be transformed. Such resources seawater, brackish/saline or contaminated groundwater, and coal seam gas water [26]. These kinds of water require an innovative technique of treatment that uses sustainable and low cost energy to produce clean water.

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Desalination of saline water is known to be one of the most sustainable alternative solutions to provide fresh water. This resource can play a significant role in socioeconomic development in many developing countries such as Africa, Pacific Asia and countries in the Middle East [16] and Latin America. Desalination is a process in which saline water is separated into two parts: one that has a low concentration of dissolved salts (fresh water), and the other which has a much higher concentration of dissolved salts than the original feed water (brine concentrate), [27]. Reverse Osmosis (RO), a conventional desalination technology, produces brine (70–55% of intake flow) depending of feed water quality; the dissolved salt concentration of the brine varies from 50 to 75 g/L resulting in a much higher density than seawater (Hamawand et al., 2013). Desalination of salty water/seawater is expensive, mostly because of the energy required [17]. However, desalination is a growing field around the world where the needs for drinkable water are crucial [2]. All conventional seawater desalination techniques such as RO, thermal distillation such as multi stage flash (MSF), electro-dialysis, or their combinations consume a large amount of energy and they do not recover the salt eventually. These techniques may also cause air pollution due to the large consumption of energy derived from fossil fuels [19,20]. Furthermore, the brine remains from these processes are huge and represent another potential environmental problem [18]. There is a potential for using algae to clean the water after amending it with some chemicals, however this has not been carried out experimentally [11]. Therefore, the utilization of renewable energy can be considered as one of energy sources of seawater desalination [3,5,17].

A complete separation of salt from salty water is something that cannot be achieved by many of the conventional methods. One conventional, most efficient and reliable method for complete separation is evaporation. Evaporation of water at atmospheric pressure requires large amounts of energy to raise the water temperature to the boiling point. In addition, at atmospheric pressure the evaporation rate is slow unless more vigorous heat is supplied. This problem can be overcome by carrying out the evaporation under reduced pressure where water can be evaporated at temperatures below its atmospheric pressure boiling point. Water evaporation under reduced pressure is energy efficient according to the laws of thermodynamics, and can be driven by low-grade thermal energy sources such as solar heat or process waste heat. While the evaporation under reduced pressure will accelerate the evaporation rate, one must be concerned with potential freezing problems [4]. Heat is required for water droplets to evaporate, heat is provided from the surrounding. Without supplemental heat there is a risk that the equipment parts get chilled and the remaining droplets freeze [1]. Carey et al. [21] conducted experiments under contract to NASA related to evaporation of water under vacuum. The set up consisted of 0.6 m^3 environmental vacuum chamber and a 250 mL beaker with 25 mL of liquid water at a temperature of 20 °C. The liquid took approximately 150 min to evaporate under reduced pressure of 0.38 kPa. In this experiment no external heat was provided neither to the liquid or the chamber.

Valuable information on desalination of seawater using solar energy has been reported, however, the desalination of sea water using vacuum spray dryer has not been fully elucidated. This study presents an innovative design for evaporation of water using renewable energy from the sun and recycles the latent heat of evaporation. Also the waste heat from the pumps and collected heat from PV panels that provide the pump with electricity are suggested as another source of energy [7,8].

2. Theory

Water such as concentrated salty water produced from other desalination processes such as RO process, brackish/saline groundwater and/or seawater can be sprayed inside a double walled glass column (evaporation column) exposed to sun light, Fig. 1. The double walled column will retain the heat inside the column and allow a full exposure to sun light. The column will be operated under reduced pressure to lower the water boiling point temperature. The generated vapour will condense on the chilled column (condensation column) attached to the double glassing evaporation column as shown in Fig. 1. This will allow the recovery of the energy (latent heat of evaporation) used to evaporate the water. After evaporating the water, the salt will end up at the bottom of the double walled column as pure dry salt.

A dark water soluble dye will be dissolved in the salty water before being introduced to the system to enhance its absorption of the sun light. Sunlight reflected or absorbed sunlight by an aerosol depends primarily on the composition and colour of the particles dissolved in it. In general, bright-coloured/translucent particles tend to reflect radiation in all directions and darker aerosols can absorb significant amounts of light [12]. Dark blue to black surfaces can absorb solar radiation to an approximate fraction of 0.8 to 0.9 of the incident radiation. A study by Gary et al. [13], showed that dispersed carbon black dust of size <0.1 μm can absorb solar energy as high as 5124.4 J/g/s (2×10^{10} cal Ib^{-1} per 10 h).

The heat required for the evaporation of the water droplets can be supplied/recovered from the following sources and sections in the process (Fig. 1); sun light, double walled insulated glassing effect, black colour effect, heat generated by the vacuum pump, heat collected from the PV panels and latent heat recovered from the generated vapour. The pump can run on solar energy using solar PV cells.

The evaporation process will be carried out under reduced pressure, in other words, this means that there will be a very small amount of air in the column. The water droplet will be released very close to the one of the opposite walls inside the middle column, to be specific it will be released next to the wall which is farther away from the sun light. This will create a smaller laminar sub-layer at that wall and will result in a higher heat transfer coefficient in comparison to the opposite wall. The fast falling of the droplet next to the wall will produce vortices (in the evaporated vapour) and turbulence which lead to reduction of the laminar sub-layer thickness, Fig. 2.

Water evaporates at a specific temperature at a specific pressure, in this design there will be three zones. The first zone is the double wall glassing that faces the sun light, the pressure inside this endclosed column will be above the atmospheric and the temperature is the highest among the whole system because it is facing the sun light. The second zone is the middle column, the pressure is below atmospheric and the temperature is almost as the same as or slightly lower than room temperature (depending on the number of droplets evaporated). The lower temperature is due to proximity of the vacuum pump and droplet evaporation. This zone can also be maintained at higher than the droplet boiling point temperature (under vacuum) if the number of the droplets is maintained in balance with the energy introduced to the system. The last zone is the vapour channel, the evaporated water from the droplets in the middle column now transports to the outside driven by the vacuum pump. The pressure inside this zone is the same as the middle column and the temperature is the lowest among the whole system. Inside this channel condensation may happen because the space available is smaller than the middle column and it is closer to the droplet. The space available inside the middle column is high enough to maintain almost constant temperature. The front side is exposed to sun light while, the other side of the wall where the vapour is transport driven by the vacuum pump has lower space which makes the change in temperature more possible, and furthermore is furthest away from the sun light.