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Study on the performance of natural vacuum desalination system using low grade heat source

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ABSTRACT

In the present work characteristics and performance of a natural vacuum desalination system using low grade heat source is studied numerically and experimentally. In the numerical work, a program to solve the governing equations in forward time step marching technique is developed. In the experimental work a lab scale natural vacuum system using electric heater as a heat source is designed and tested. The surface area of seawater in the evaporator is 0.5 m. The numerical and experimental results show a good agreement. By using numerical simulations effect operating conditions such as heat source temperature, condenser temperature, heating coil surface area, and the present of heat recovery unit are explored. The simulation showed that, the present system with evaporator surface area of 0.2 m^2, operation time of 9 h and source temperature of 80 °C will produce 6.63 L of fresh water ant thermal efficiency is 70.4%. The main conclusion can be drawn here is that the performance of the natural vacuum desalination system is mainly affected by maximum temperature in evaporator and minimum temperature in condenser. On the other hand, the surface area of heating coil and the heat recovery unit showed only a small effect.

1. Introduction

Demand for fresh water is increasing due to industrialization, life standard, depletion of natural resources, etc. According to United Nation Organization that by the year of 2025, almost 1800 million people around the world will be under severe water scarcity [1]. Desalination of seawater can be used to fill this demand. The desalination system is not a new technology. In the present, many regions in world such as countries in the Middle East, Arabic countries, North America, some of Asian countries, Europe, Africa, Central America, South America and Australia have been doing desalinations to meet their need on fresh water [2]. There several methodologies of desalination such as multi-stage flash, multi-effects distillation, vapor compression, reversal osmosis, and electro-dialysis are already known. The conventional desalination systems in services mainly use fossil fuel. According to a study by Kalogirou [3], about 10,000 t of fossil fuel was burn to power desalination systems in the world.

Those facts motivate researchers to perform research on desalination systems in order to develop a more efficient system and or to enhance the using of renewable resources or waste heat [4]. Renewable energy resources that usually used to power desalination are solar energy, wind power, and geothermal energy. Among these three, the most used is solar energy which is up to 57% [2]. It is predicted that in the future, desalination powered by solar energy (named as solar desalination), will be more popular. Even the countries with big oil producer such as Saudi Arabia are enhancing the use of solar energy to power their desalination systems in order to develop the sustainable desalination system. Several researchers have published their work on the innovations of desalination powered by renewable and waste heat. Gude et al. [5] reported a feasibility study of a new two-stage low temperature

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desalination. The field test results showed that the two-stage desalination process has potential for standalone small to large scale applications in water and energy scarce rural areas with specific energy consumption of 15,000 kJ/kg of fresh water. If it is operated by solar energy the desalination costs are less than $ 7/m^3 fresh water. Li et al. [6] proposed a system that combines multi effect distillation desalination with a supercritical organic Rankine Cycle and an ejector. Their system works like a combined heat, power and condensation. The thermal performance of the system is analyzed theoretically. The results show overall exergy efficiency close to 40% for salt concentration of 35 g/kg using a low temperature heat source at 150 °C.

Araghi et al. [7] reported an analytical study on the performance of a new combined vacuum desalination and power system as a heat recovery. The system is claimed can run on waste heat and an organic working fluid. The results show that the overall performance of the introduced system is comparable with the discharge thermal energy combined desalination system utilizing ammonia mixture. However in term of desalination, the proposed system produces more fresh water. Gao et al. [8] performed an experimental study on water separation process in a novel spray flash vacuum evaporator with heat-pipe (HP). Parametric studies are carried out, such as cold source and heat source temperature, spray temperature, and spray flow. The results show that the maximum heat flux density reaches 32 W/cm^2 on evaporator bland plate. The HP absorbs energy effectively from low grade heat source then transfer the energy to the droplets already flashed, so as to maintain or even increase the superheat degree of droplets during the evaporation process. Some conclusions of the study are the heat source temperature is determinant of fresh water yield. The higher heat source temperature is the more heat that droplets can obtain and the faster evaporation process will be. And the cooling water temperature is an important factor of fresh water yield. Dow et al. [9] report an experimental study on a pilot plant of direct contact membrane distillation (DCMD) driven by low grade waste heat: membrane fouling and energy assessment. The pilot plant was located at a gas fired power station which provided the heat source (lower than 40 °C) and waste water to the DCMD system with 0.67 m^2 of membrane area. Based on the available energy for a continuously operating 500 MW (electric) rated power station, the treatment potential was estimated at up to 8000 kL/day.

Christ et al. [10] report a study on the comparison of a boosted multi-effect distillation (MED) for sensible low-grade heat source with feed pre-heating multi-effect distillation. The results show that for most operational conditions germane to sensible waste heat source and renewable energies, the boosted MED system offers both thermodynamic and economic superior performance, especially when low heating media temperatures prevail. Gude [11] discusses current energy storage options for different desalination technologies using various renewable energy and waste heat source with focus on thermal energy storage system. Bundschuh et al. [12] identify different types and low-cost low-enthalpy (50–150 °C) geothermal heat sources and evaluate their potentials and their suitability for water desalination and treatment using conventional technologies for different scales and situation. The results suggest that geothermal option is superior to the solar option if low-cost geothermal option is available because it provides a constant heat source in contrast to solar. Ciocolanti et al. [13] performed an experimental study on the performance behavior of small scale single effect thermal desalination plant. The prototype consists of a 1 kWe Stirling engine coupled with a single effect thermal desalination plant for the simultaneous production of electricity and > 150 L/day of fresh water.

One of the promising solar desalination is natural vacuum desalination system. In the system seawater is placed in a container which is vacuumed naturally by using the gravity of the water. The advantage of using the vacuum is that a low grade heat source such as solar energy can be used efficiently. Several researches of natural vacuum desalination have been reported in literature. Al-Kharabsheh and Goswani [14,15] reported the research on preliminary experimental and theoretical analysis of a natural vacuum water desalination system using low-grade solar heat. The effects of several various operating conditions were studied. Simulation for Gainesville, Florida, the daily output from a system of 1 m^2 of evaporator area with 1 m^2 of solar collector area could reach 6.5 kg fresh water. In order to increase the performance of the natural vacuum desalination system several modifications have been proposed. Gude et al. [16] reported a study on vacuum desalination system and it was coupled with solar collector of 18 m^2 and thermal energy storage with a volume of 3 m^3. The system is capable of producing 100 L/day fresh water. Gude and Nirmalakandan [17] use the same solar desalination system and combined it with a solar-assisted air-conditioning system. The results showed that cooling capacity of 3.25 kW and distillate yield of 4.5 kg/hour can be obtained. Maroo and Goswani [18] proposed natural vacuum flash desalination system operation using in single stage mode and two stage mode. With a solar collector of 1 m^2 area, the proposed system produces nearly 5.54 kg and 8.66 kg of distillate while operating in single stage and two stage modes with a performance ratio of 0.748 and 1.35, respectively. Ayhan and Al-Madani [19] proposed a natural vacuum desalination that consists of evaporator column exposed to solar radiation and shaded condenser column. Here a blower is proposed to move the vapor from evaporator to condenser.

Those reviewed studies showed that study on the desalination has come under scrutiny. Among those desalination technologies, the present paper focuses on the natural vacuum system. However, the performance of the natural vacuum solar needs to be increased. Thus several modifications are extremely needed. To propose a good modification the mechanism and characteristics of the natural vacuum desalination should be explored more. In this work numerical and experimental study on a lab scale natural vacuum desalination will be carried out. The main objective is to explore the operational characteristics of the natural vacuum desalination system. The numerical method will be used to perform a case study in order to explore the main parameter that affect the performance of the system. The results of the present study are expected to supply the necessary information in the developing high performance solar desalination system.

2. Problem formulation

The schematic diagram of the analyzed natural vacuum desalination system is shown in Fig. 1. The system consists of heating unit, evaporation unit, and condensing unit. The heating unit is originally designed for solar collector system. However, to make an