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Performance analysis of a low-temperature waste heat-driven adsorption desalination prototype

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ABSTRACT

This paper discusses the performance analysis of an advanced adsorption desalination (AD) cycle with an internal heat recovery between the condenser and the evaporator. The AD cycle employs the adsorption–desorption principles to convert sea or brackish water into high-grade potable water with total dissolved solids (TDS) less than 10 ppm (mg/L) utilizing low-temperature heat source. The salient features of the AD cycle are the utilization of low temperature waste heat (typically 55 °C to 85 °C) with the employment of an environment-friendly silica gel/water pair and the low maintenance as it has no major moving parts other than the pumps and valves. For improved performance of the AD pilot plant, the internal heat recovery scheme between the condenser and evaporator has been implemented with a run-about water circuit between them. The efficacy of the scheme is analyzed in terms of key performance indicators such as the specific daily water production (*SDWP*) and the performance ratio (*PR*). Extensive experiments were performed for assorted heat source temperatures ranging from 70 °C to 50 °C. From the experiments, the *SDWP* of the AD cycle with the proposed heat recovery scheme is found to be 15 m^3 of water per ton of silica gel that is almost twice that of the yield obtained by a conventional AD cycle for the same operation conditions. Another important finding of AD desalination plant is that the advanced AD cycle could still be operational with an inlet heat source temperature of 50 °C and yet achieving a *SDWP* of 4.3 m^3 – a feat that never seen by any heat-driven cycles.

1. Introduction

Water is the basic substance of life on earth and is directly related to the sustainability and the development of an economy. Much water is needed for agriculture, industry, recreation and human consumption [1–3]. Statistically, three-quarters of the earth' surface is covered by water [4], however, most of the water available to human beings is unusable due to the high salinity, typically, total dissolved solids (TDS) higher than 35,000 mg/L. According to World Health Organization (WHO) drinking water standards, water with TDS less than 1000 ppm is considered to be drinkable [5,6]. However, over 97.5% of the earth's water represents oceans or sea with TDS value much higher than the potable TDS range. Besides, 80% of the remaining 2.5% fresh water is frozen in the icecaps or combined as soil moisture [7]. On the other hand, Global potable water demand has been increasing with economical and industrial growth. Concurrently, fresh water requirement for food production increases exponentially with drastic increase in population [8–10]. WHO report states that at least one billion people do not have access to clean and fresh water, and about 41% of Earth's population live in the water-stressed areas, and this deprived population may climb to 3.5 billion by the year 2025 [11]. Meanwhile, fresh water demand of the world is expected to be at 2% growth rate to 6900 billion m^3 (Bnm^3) in 2030 from today's 4500 Bnm^3, while the existing sustainable supply from the Earth's natural water cycle is only 400 Bnm^3 [12,13].

Desalination can be considered a practical solution to daily water crisis in the regions where the annual rainfall is significantly low and no fresh water is available within a reasonable distance. Desalination methods can be categorized into three major groups, namely: (i) thermally-activated systems which utilize thermal energy to produce fresh water from sea or brackish water by evaporation and then condensing the vapor, (ii) pressure-activated systems which extract potable water from the salt water applying excess osmotic pressure across a semi-permeable membrane which selectively allows the passage of fresh water but retarding

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Nomenclature

c_p	specific heat capacity (J/kg K)
h_{fg}	latent heat of vaporization (J/kg)
M_{sg}	mass of adsorbent (silica gel) (kg)
$\dot{m}$	mass flow rate (kg/s)
τ	No. of operating cycle/day (–)
D_{s0}	a kinetic constant for the silica gel water system (m^2/s)
E	activation energy of surface diffusion (kJ/kg)
n	index of the Dubinin-Astakhov isotherm model (–)
p	pressure (Pa)
P_0	reference pressure (Pa)
Q	power (W)
q	uptake by the adsorbent material (kg/kg)
q^*	the equilibrium uptake (kg/kg)
q^0	the limiting uptake (kg/kg)
R	gas constant (J/kg mol)
R_p	average radius of silica gel (mm)
T	temperature (°C)
t	time (s)
t_{cycle}	cycle time (s)

Subscripts

ads	adsorption
cond	condenser
cool	cold water
des	desorption
hot	hot water
in	inlet
load	load surface at the evaporator
out	outlet

the dissolved salts and (iii) chemically-activated desalination methods which include ion-exchange desalination, liquid–liquid extraction, and gas hydrate or other precipitation schemes [14–20]. Among desalination technologies, the RO technology represents 59% of total 14,451 desalination plants with 60 million cubic meters per day desalination capacity of the world while the MSF has 27% share [21–23]. Another type of desalination method that utilizes the electrochemical process includes the Electrodialysis (ED) and Electrodialysis Reversal (EDR) where ions migrate through ion-selective semipermeable membranes due to their attraction to electrically charged electrodes [24,25]. Besides, recent developments in the Multi-Effect Distillation (MED) system coupled with the Mechanical Vapor Compressor (MVC) or Thermal Vapor Compressor (TVC) have improved the performance. However, the improvement in the water production rate is subject to the available number of effects that depends on the temperature difference between the Top Brine Temperature (TBT) and the down condenser temperature which is limited by the condenser temperature where seawater is usually the case [26–28]. Thus, the evaporation temperature of the saline cannot be below 35 °C in most cases. Moreover, almost all the desalination systems suffer from at least two inherent drawbacks i.e., high energy intensive and/or prone to fouling and corrosion to the evaporation or separation unit of the sea water [29,30].

Adsorption desalination (AD) cycles utilize the sorption phenomena of the adsorbate/adsorbent pair to produce potable water from sea or brackish water. Adsorption desalination cycles are designed to mitigate the shortcomings of conventional desalination methods [31]. The AD cycle mimics the evaporation in the ambient by low-temperature waste heat of the sun, and condensing the water vapor at high altitude, producing pure water with no input of fossil fuel or energy from carbon-based energy. In AD cycles, the evaporation of the saline water occurs at low-temperatures typically between 5 °C and 20 °C. The operating regime for the AD cycle on the calcium sulfate solubility verses temperature is given in Fig. 1 [32]. It is noted that the low-temperature evaporation of the saline water allows AD cycle to achieve high recovery ratio while operating outside the solubility limit. Thus, scaling to the evaporating units can be reduced in AD cycle.

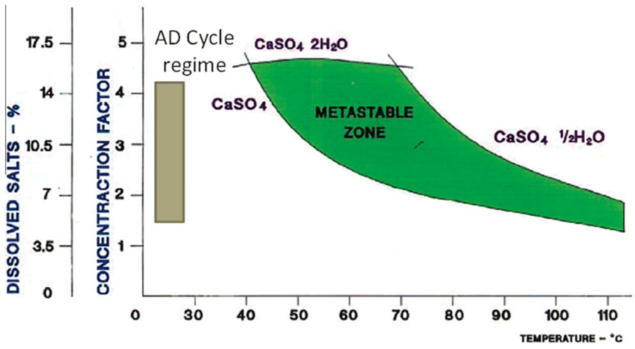

Fig. 1. Operation regime of AD cycle on calcium sulfate solubility diagram [32].

The earliest development on adsorption-based desalination was reported by Broughton [33], using an ion-retarded resin for the vapor uptake, where a process with a thermally-driven two-bed configuration is simulated. Similar theoretical studies on the adsorption desalination plant were also proposed by Zejli et al. [34], Al-kharabsheh and Goswami [35,36]. Solar heat source was studied as a heat source for the desalination plant, combined with an open-cycle adsorption heat pump using zeolite as the adsorbent material. Wang and Ng investigated the performance of the AD cycle using a four-bed regeneration scheme and reported an optimal specific daily water production (*SDWP*) of 4.7 kg/kg silica gel [30]. A number of studies have been reported on the AD cycle highlighting the theoretical model, the numerical simulation, the operation strategy at various regeneration temperatures as well as the performances across assorted heat source temperatures [37–41].

In this paper, the performance of the advanced AD cycle with the implementation of the internal heat recovery between the condenser and evaporator is presented. The internal heat recovery is achieved by a water run-about circuit between the evaporator and condenser. The results are augmented with a conventional AD cycle where the inlet temperatures to the evaporator and condenser are fixed depending on the ambient or external heatsource, and an advanced cycle with internal heat recovery between the condenser and the evaporator.

2. Description of the advanced AD cycle

The schematic diagram of an advanced AD cycle is shown in Fig. 2. The major components of the AD cycle are the evaporator, the condenser and the adsorber beds. Sea water is de-aerated in the de-aeration tank prior to the charging into the evaporator. The evaporator is connected with one or a pair of adsorber beds during adsorption phase. The adsorbent material (hydrophilic mesoporous silica gel) inside the adsorber bed triggers adsorption process lowering the pressure inside the adsorber and the evaporator.