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Numerical simulation of combined adsorption desalination and cooling cycles with integrated evaporator/condenser

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HIGHLIGHTS

- A 4 bed combined adsorption desalination and cooling cycles is modelled.
- Effect of Condenser temperature is studied.
- 3 operating modes can produce various amounts of water & cooling according to needs.
- Can produce more water than any system along with cooling at low evap. temp. (10 °C).

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ABSTRACT

The availability of potable water and cooling are becoming increasingly important to ensure good sustainability and quality of life. In this work, a new multi-cycle adsorption desalination and cooling system using AQSOA-Z02 has been developed for high water production and cooling rates using renewable and waste heat sources. It consists of two 2-adsorber bed cycles linked with integrated evaporator/condenser, one cycle uses the integrated evaporator/condenser as evaporator (upper) and the second one uses it as a condenser (lower). In this system low condensing temperatures can be achieved using the cooling effect from the evaporator of the lower cycle and the integrated evaporator/condenser thus enhancing the system performance. Also, the adsorber beds of the upper and lower cycles are heated in series during the desorption process using the same heat source. This system can operate in three modes depending on the desalinated water and cooling capacity requirements. Results showed that the specific daily water production ranges from 6.64 to 15.4 m^3/tonne adsorbent/day while the cooling capacity reaches up 46.6 Rton/tonne adsorbent at evaporator temperature of 10 °C. The new cycle offers potential of simultaneously producing large amounts of desalinated water and cooling capacity (at 10 °C) compared to other cycles.

1. Introduction

In the past few years, adsorption desalination technology has shown potential as a possible alternative for other desalination technologies [1, 2]. This technology can utilize low temperature waste heat to produce two useful effects; desalination and cooling. It can produce fresh water with low salinity of 10 ppm with minimal running cost of 0.2 \$/m^3 and CO_2 emissions of 0.6 kg/m^3 [3]. Adsorption desalination system is a thermodynamic cycle that consists of evaporation/adsorption and desorption/condensation processes where the adsorbent material adsorbs pure water vapor from the boiling seawater in the evaporator. This evaporation process is maintained by the adsorbing action of the adsorbent while external heat load in the form of flowing water in a coil, is used to stabilize the evaporation temperature. During this adsorption process, cooling fluid is needed to absorb the rejected heat of adsorption while in the desorption process, heating is applied to regenerate the adsorbed water vapor using waste heat or solar energy at low temperature. The desorbed water vapor is condensed in the condenser to produce potable water which is collected and pumped out of the condenser. Cooling effect is produced during the evaporation process which occurs at temperature ranging from 10 to 30 °C [4].

Jun et al. [5,6] studied theoretically and experimentally the effect of evaporator temperature relative to cooling water temperature on the performance of the cycle where cooling water temperature is the same for adsorbing bed and condenser. The cycle was studied for various evaporator temperatures higher, equal and lower than that of the cooling water. Results showed that when the evaporator temperature is below the cooling water temperature, the water production rate increases as the evaporator temperature increases while the energy consumption decreases. However, when the evaporator temperature is equal or higher than the cooling water temperature, the water

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Nomenclature

c	uptake ($kg \cdot kg^{-1}$)
c^*	equilibrium uptake ($kg \cdot kg^{-1}$)
cp	specific heat at constant pressure ($kg \cdot kg^{-1} \cdot K^{-1}$)
COP	coefficient of performance (−)
h	enthalpy ($kJ \cdot kg^{-1}$)
M	mass (kg)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)
n	adsorption/desorption phase, flag (−)
OCR	overall conversion ratio (−)
P	pressure (kPa)
PR	performance ratio (−)
Q_{st}	isosteric heat of adsorption (kJ/kg)
SCP	specific cooling power ($kW \cdot kg^{-1}$)
$SDWP$	specific daily water production ($m^3/t\ day^{-1}$)
T	temperature (K)
X	salt concentration (ppm)
θ	seawater charging flag (−)
γ	brine discharge flag (−)
τ	no of cycles per day (−)

Subscripts

a	adsorbent material
ads	adsorption
$cond$	condenser
cw	cooling water
D	vapor
d	distillate water
des	desorption
$evap$	evaporator
f	liquid
hw	heating water
HX	heat exchanger
in	inlet
ads	adsorber bed
des	desorber bed
out	outlet
s	seawater
t	time

production and energy consumption are not affected by the evaporator temperature.

Thu et al. [7], have studied experimentally the performance of a silica gel adsorption desalination system that operates on either two or four bed configurations. Water production, cycle time and performance ratio were investigated at different heat source temperatures and constant heat sink temperature. Experimental results showed that at low heat source temperature, a longer cycle time is required for the production of maximum amount of fresh water. Measurements showed that maximum water production achieved was 10 m^3 per day per tonne of silica gel at a performance ratio of 0.61 in the case of operating the cycle with four bed master-slave configuration. A significant improvement in specific daily water production (SDWP) was achieved compared to the 2 bed configuration which resulted in 8.79 m^3/day per tonne of silica gel.

Ng et al. [8], have developed a mathematical model for a 4 bed adsorption system using silica gel/water pair to produce both cooling and desalinated fresh water. At different hot and chilled water temperatures, cycle performance was analyzed by calculating specific cooling power (SCP), SDWP, and overall conversion ratio (OCR). It was found that a silica gel adsorption system can produce 8 m^3/day and 51.6 Rton per tonne of silica gel when optimized for water production at evaporator temperature of 30 °C or 3.8 m^3/day and 22 Rton per tonne of silica gel at evaporator temperature of 10 °C. In addition, the cycle can reach a maximum OCR of 1.4. Ng et al. [9], carried experimental testing of the modeled cycle and results showed that chilled water at 7 to 10 °C with a specific cooling capacity (SCC) of 25–35 Rton/tonne of silica gel can be produced in addition to a SDWP of 3–5 m^3 per tonne of silica gel per day while the OCR is about 0.8–1.1.

Youssef et al. [10], have numerically studied the effect of evaporator and condenser water temperature on the performance of a silica-gel 2-bed cycle. Simulation results showed that as the condenser temperature decreases and evaporator temperature increases, cycle water production and cooling effect increase. A water production of 10 m^3/tonne adsorbent /day and cooling effect of 77 Rton/tonne of adsorbent were achieved at condenser and evaporator water inlet temperatures of 10 °C and 30 °C, respectively.

Youssef et al. [11], have compared numerically the performance of a 2-bed adsorption cycle using AQSOA-Z02/water pair with the same cycle using silica-gel/water. Effect of evaporator water temperature on cycle performance in terms of SDWP and coefficient of performance (COP) was studied. Results showed that AQSOA-Z02 is better for chilled water temperatures below 20 °C as 5.8 m^3 of fresh water per day and 50.1 Rton of cooling can be produced compared to silica-gel that can produce only 2.8 m^3 of fresh water per day and 17.2 Rton of cooling at the same operating conditions. However, silica-gel proved to be superior above 20 °C as it can reach SDWP of 8.4 m^3 and 62.4 Rton of cooling.

Alam et al. [12], have proposed an advanced adsorption refrigeration cycle consisting of 4 beds comprising of two 2-bed adsorption refrigeration cycles, upper and lower. A mass recovery scheme is applied between the beds in the upper and lower cycles in addition to heat recovery for the heating source between the two cycles. The results of the mathematical model showed that SCP and coefficient of performance (COP) reached 14.3 Rton/tonne adsorbent and 0.6 respectively compared to performance of the 2-bed cycle which resulted in 5.95 Rton/tonne adsorbent and 0.35 for SCP and COP respectively at the same regeneration temperature of 65 °C and based on cycle time of 1200 s. However, at hot source temperatures above 70 °C, the COP of the advanced cycle is lower than that of the 2-bed cycle but resulted in higher cooling effect than two stage chiller. Also, the proposed system can be converted to two-stage chiller mode to make it able to cover wider range of heat source temperatures for the production of effective cooling.

Thu et al. [13], have developed an advanced 2-bed adsorption desalination cycle that contains an integrated evaporator-condenser device for better heat transfer. Numerical simulations were used to predict the performance of a silica gel cycle operating in a 2 bed mode. It was found that using this cycle configuration increases the evaporator temperature and vapor pressure in the adsorber beds because of recovery of condenser heat. Results showed that SDWP improved by 300% compared to the conventional adsorption desalination cycle as it reached 26 m^3/day per tonne of silica gel instead of 8 m^3/day per tonne of silica gel. Moreover, lower specific electricity consumption were achieved at 1.38 kWh/m^3 as pumping power was reduced due to dispensing of evaporator and condenser cooling water circulations.

Table 1 compares various adsorption systems that were reported to produce desalination and cooling where different parameters are shown including adsorbent material, system type, amount of water produced per day and amount of cooling produced. From this comparison, it was found that the highest amount of fresh water produced was 10 m^3/tonne adsorbent/day when silica gel RD type was used [7]. However, it reached 26 m^3/tonne adsorbent/day when advanced silica gel A++ type [14] was used at high evaporator temperature of 42 °C (not suitable for cooling applications) in an advanced adsorption desalination cycle [13]. For water desalination and cooling, a maximum of 10 m^3/tonne adsorbent/day of water was produced with 77 Rton/tonne adsorbent of cooling [10] when silica gel RD type was used at 10 °C condensing temperature and at high evaporating temperature of 30 °C. In case of cooling production at low evaporator temperature, 10 °C, a maximum of 53.7 Rton/tonne adsorbent of cooling and 6.2 m3/tonne adsorbent/day of water were produced when AQSOA-Z02 was used [15]. Finally, the