

Performance investigation on a 4-bed adsorption desalination cycle with internal heat recovery scheme



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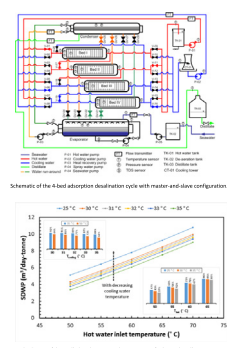
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HIGHLIGHTS

- Multi-bed AD cycle with internal heat recovery between the condenser and the evaporator
- Model captures reversed adsorption/desorption phenomena associated with switching periods.
- Experimental data for such cycle is reported for the first time using 50 °C to 70 °C heat source.
- Performance comparison for different types of Adsorption Desalination cycles

GRAPHICAL ABSTRACT



Schematic of the 4-bed adsorption desalination cycle with master-and-slave configuration.

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ABSTRACT

Multi-bed adsorption cycle with the internal heat recovery between the condenser and the evaporator is investigated for desalination application. A numerical model is developed for a 4-bed adsorption cycle implemented with the master-and-slave configuration and the aforementioned internal heat recovery scheme. The present model captures the reversed adsorption/desorption phenomena frequently associated with the unmatched switching periods. Mesoporous silica gel and water vapor emanated from the evaporation of the seawater are employed as the adsorbent and adsorbate pair. The experimental data and investigation for such configurations are reported for the first time at heat source temperatures from 50 °C to 70 °C. The numerical model is validated rigorously and the parametric study is conducted for the performance of the cycle at assorted operation conditions such as hot and cooling water inlet temperatures and the cycle times. The specific daily water production (SDWP) of the present cycle is found to be about 10 m³/day per tonne of silica gel for the heat source temperature at 70 °C. Performance comparison is conducted for various types of adsorption desalination cycles. It is observed that the AD cycle with the current configuration provides superior performance whilst is operational at unprecedentedly low heat source temperature as low as 50 °C.

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Nomenclature

A	area, m ²
C	concentration, kg/kg
C^*	equilibrium uptake, kg/kg
C_0	the limiting uptake, kg/kg
COP	the coefficient of performance, (–)
c_p	specific heat capacity, kJ/(kg·K)
D_{so}	kinetic constant for the silica gel water system, m ² /s
E	activation energy of surface diffusion, kJ/mol
h	enthalpy, kJ/kg
h_{fg}	latent heat, kJ/kg
\dot{m}	mass flow rate, kg/s
n	surface heterogeneity (–)
N_{bed}	number of adsorber bed (–)
p	pressure, Pa
p_0	equilibrium pressure, Pa
PR	the performance ratio, (–)
Q	rate of energy transfer, W
q	total heat or energy, kJ/kg
q_{st}	isosteric heat of adsorption, kJ/kg
R	gas constant, J/(kg·mol)
R_p	average radius of silica gel, m
$SDWP$	specific daily water production, m ³ /(day·tonne of silica gel)
T	temperature, K
t	time, s
T_0	reference temperature, K
U	overall heat transfer coefficient, W/(m ² ·K)
v	specific volume, cm ³ /g
w_{sg}	mass of silica gel per bed, kg

Subscripts

a	adsorbate or adsorbed phase
$cond$	condenser
cw	cooling water
$cycle$	operation cycle
d	distillate/condensate
$evap$	evaporator
evc	evaporator condenser heat recovery circuit
f	liquid phase
g	gaseous phase
hw	hot water
HXA	adsorber bed heat exchanger assembly
HXC	condenser heat exchanger assembly
HXE	evaporator heat exchanger assembly
In	inlet
$mads$	master adsorption/adsorber
$mcond$	condenser associated with master desorption/desorber
$mdes$	master desorption/desorber
$mdsu$	desuperheating associated with master desorption/desorber
$mevap$	evaporation associated with master adsorption/adsorber
Out	outlet
$sads$	slave adsorption/adsorber
$scond$	condenser associated with slave desorption/desorber
$sdes$	slave desorption/desorber
$sdsu$	desuperheating associated with slave desorption/desorber
$sevap$	evaporation associated with slave adsorption/adsorber
sg	silica gel
v	vapor
w	water

1. Introduction

Adsorption desalination (AD) systems have gained considerable attention recently due to their capabilities to be operational at low driving heat source temperatures [1–3]. The AD cycles produce two essential commodities namely the cooling power and the potable water, simultaneously [4–7]. Furthermore, the ultra-pure potable water is produced even from highly concentrated brine solution with TDS more than 200 g/L whilst the recovery ratio can be as high as 80% [8]. Such AD cycles essentially utilize the heat pump concept shifting the heat from the low temperature reservoir to the higher one. The low temperature reservoir is normally utilized as the source for evaporating the saline water and producing cooling power whilst the condenser is employed for the potable water production.

The adsorbent for AD cycles essentially requires to be porous material with huge surface areas and hydrophilic for efficient water vapor uptake. The pore surface area with more than 500 m²/g is preferable for the effective adsorption of water vapor and the compactness of the system. Silica gels have been the de facto choice whilst zeolite based adsorbents such as AQSOA-Z01, AQSOA-Z02 have been employed in AD cycles lately [9–13]. In some cases, multiple adsorbents are proposed to be utilized in one system and such work has been proposed by Ali et al. [14] whilst Youssef et al., have conducted the comparison of the AD cycle using silica gel and AQSOA-Z02 as adsorbents [15].

However, the thermodynamic and the batch-type nature of the interaction between the solid adsorbent and the vapor adsorbate calls for performance improvement schemes such as heat and mass recovery schemes. Various configurations and effects of operational conditions on the performance of the AD cycle have been studied over the past few years such as multi-bed, multi-stage with a couple of heat and mass recovery schemes. Multi-bed approach has been developed and studied by numerous researchers for the production of both cooling and desalination [16–18]. Wang et al., has reported the heat and mass recovery scheme by pressure equalization between the adsorber beds whilst Sharkawy et al., reported the experimental investigation on the performance improvement of the AD cycle [19,20]. Thu. et al., evaluated the optimized cycle times for AD system at various hot water inlet temperatures [21] and Wu et al., studied three possible cases of the thermodynamic cycles on AD system for possible evaporator temperatures relative to the cooling water temperature [22,23]. Mitra et al., has reported the performance of the AD cycles in single and 2-stage modes with air-cooled systems [24] whilst Saha et al., have developed AD systems for the simultaneous production of potable water and cooling power at two-level of temperatures using 3-bed 2-evaporator approach [25,26].

Thu. et al. has pioneered the hybrid Adsorption Desalination cycle with Multi Effect Distillation or simply the ADMED cycles for improved desalting performance powered by low-temperature heat sources [27–29]. In this configuration, two heat sources are required for the MED system and AD system. Shahzad et al., have later conducted experiments on such cycles using a 3-effect MED systems [30,31]. Recently, Thu. et al., have introduced a novel multi-effect adsorption desalination, the MEAD cycle, where the energy from the desorbed vapor is recovered for multiple evaporation and condensation giving remarkably high performance ratio with improved water production [32]. This cycle utilizes only a single heat source to the desorber bed whilst almost all the effect operates below ambient temperatures [33]. The efficacy of such cycle is experimentally verified by Shahzad et al. using the same experimental facility [34].

Internal heat recovery scheme from the condenser to the evaporator of the AD cycle is first reported by Thu et al. with two possible configurations: namely (1) a consolidated evaporator-condenser device and (2) a heat recovery circuit running across the evaporator and the condenser [6,35–39]. Youssef et al. have reported the numerical simulation on AD cycle with such heat recovery schemes [40]. However, the numerical analysis with the experimental confirmation has not been

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