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Thermodynamic analysis of an adsorption-based desalination cycle

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ABSTRACT

Adsorption-based desalination (AD) is attracting increasing attention because of its ability to co-generate double-distilled fresh water and cooling. In this paper, a thermodynamic model has been developed in order to study the factors that influence the fresh water production rate (FWPR) and energy consumption of an adsorption-based desalination system. Water adsorption on the silica gel adsorbent is modelled using a Langmuir isotherm and the factors studied are the silica gel adsorption equilibrium constant and the temperatures of the hot and cooling water which supply and extract heat from the silica gel respectively.

Keywords: Adsorption desalination; Silica gel-water; Isotherms; Adsorption chiller

1. Introduction

Rising water scarcity due to climate change and over-exploitation of traditional water resources is of increasing concern across the world, both because of its economic implications as well as the continued habitability of long-standing communities. One solution to this issue is desalination of saline or brackish water, which has long been used in regions that have traditionally faced water shortages such as the Middle East. There are several ways in which desalination – which is defined as separation of excess salt and other minerals from water molecules – is carried out, including multi-effect, multi-stage flash and membrane-based reverse osmosis (RO) desalination, which are all exploited commercially (Zejli et al., 2004; Mosry et al., 1994; Awerbuch et al., 1989; Wazzan and Al-Modaf, 2001; Bruggen and Vandecasteele, 2002; Al-Shammiri and Safar, 1999; Buckley et al., 1993).

Adsorption-based desalination (AD) uses low temperature waste heat to inexpensively desalinate saline and brackish water to produce potable water for both industrial and residential applications (Wang and Ng, 2005). There are five significant advantages of the AD compared with more traditional desalination techniques (Wang and Ng, 2005; El-Sharkawy et al., 2007 Wang et al., 2007): (1) fewer moving parts, which reduces maintenance costs, (2) reduced fouling and corrosion due to the low operating temperature and confinement of the saline/brackish solution to a fraction of the total system, (3) ability to co-generate potable water and cooling, (4) double distillation – the desalination process minimizes the possibility of so-called '(bio) gen-contamination', and (5) ability to treat/desalinate saline water containing organic compounds.

Adsorption-based desalination has received very little attention in the literature despite its considerable advantages. Ng and co-workers (Wang and Ng, 2005; Wang et al., 2007; Thua et al., 2009; Ng et al., 2009) have investigated in detail the performance of a pilot scale adsorption-based desalination system as a function of system configuration and operating parameters. This group (Chua et al., 1999, 2004) and others (Wang et al., 2005; Wang and Chua, 2007) have also developed and used a lumped dynamic model of adsorption desalination to study the dynamic behaviour of adsorption desalination systems as a function of operating parameters such as the cycle time. In order to more fully probe the effect that thermal parameters and adsorbent properties have on the performance of adsorption-based desalination, we have undertaken a comprehensive thermodynamic analysis of an AD cycle based on a silica gel adsorbent.

The paper first outlines in detail the thermodynamic model along with details of the adsorbent and other conditions used in the study. Results obtained from the model are

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Nomenclature

C	specific heat (kJ/(kg K))
h	enthalpy (J/kg)
K_0^I	adsorption equilibrium constant
k_a	adsorption rate constant
k_d	desorption rate constant
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
X	fraction of amount adsorbate adsorbed by the adsorbent at equilibrium condition (kg/kg dry adsorbent)
X_0	fraction of amount adsorbate which can be adsorbed by the adsorbent under equilibrium condition (kg/kg dry adsorbent)
Q	heat of desorption (kJ/kg)
Q_{st}	isosteric heat of adsorption (kJ/kg)
R	universal gas constant (kJ/(kg K))
T	temperature (°C)
ΔH^θ	standard enthalpy change (kJ/kg)
EC	energy consumption for 1 kg water (kJ/kg)

Superscripts/subscripts

ads	adsorption
bed	adsorption or desorption bed
chilled	chilled water
cond	condenser
des	desorption
evap	evaporator
fg	enthalpy change
heating(*bed*)	bed heating capacity
cooling(*bed*)	bed cooling capacity
hot	hot water
in	inlet
out	outlet
sg	silica gel
water	water
$1 \rightarrow 2$	state 1 to state 2
$2 \rightarrow 3$	state 2 to state 3
$3 \rightarrow 4$	state 3 to state 4
$4 \rightarrow 1$	state 4 to state 1

then presented, including the effect the silica gel adsorption equilibrium constant and the temperatures of the hot and cool water (which supply and extract heat from the silica gel respectively) have on the fresh water production rate (FWPR) and energy consumption of AD under the equilibrium assumption. We conclude with a comment about future work.

2. Working principle

Fig. 1 shows a schematic of a two-bed adsorption-based desalinator, which is the most basic form of such a system. This system consists of three major components: the condenser, the (silica gel) beds, and the evaporator. After the whole system is degassed and the saline/source water is charged into the evaporator, with valve 1 open, the source water evaporates and travels from the evaporator into bed 1 where it is adsorbed by the silica gel as the heat liberated by the adsorption is removed by the cooling water circulating in the manifold of bed 1. Once bed 1 is saturated with water vapour, valve 1 is closed and valve 2 is opened. At the same time, the circulating water in bed 1 is switched to hot water. The hot water drives off the water adsorbed on (i.e. regenerates) the silica gel to the condenser where it is finally condensed and harvested as pure water. Once the temperature of bed 1 peaks, the silica gel regeneration process ceases and the cycle for the bed is ready to re-start. Beds 1 and 2 are operated alternatively in this way to produce fresh water (and cooling capacity from the evaporator) in a continuous manner.

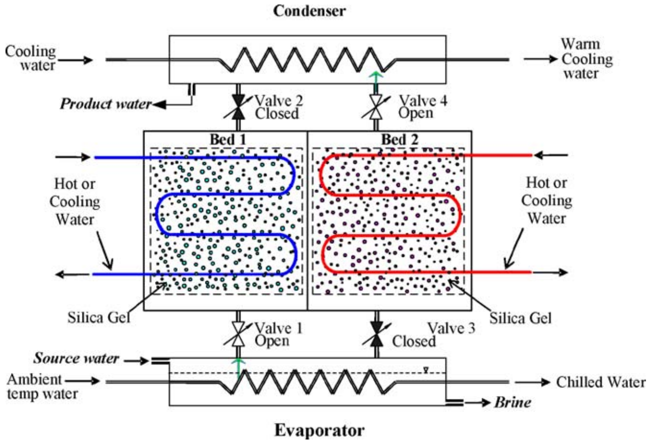

Fig. 1 – Schematic of a two-bed adsorption desalination system. Refer to text for a description of its operation.

It should be noted that the fresh water is distilled twice (i.e. double-distilled). At the same time, a cooling effect is created by the evaporator, which can be used for air conditioning purposes as in a normal adsorption chiller, or be fed back to the bed or condenser. In other words, the adsorption desalination system has the ability to perform as a chiller and double-distilling desalinator simultaneously. Silica gel is a popular adsorbent because it is able to take-up significant levels of water (up to 40% by mass) (Ng et al., 2001) without significant structural or volume change and readily release it under mild heating (Chakraborty et al., 2009). To improve energy efficiency, in practice systems with two or more beds are used (Chua et al., 1999). However, in this study, consideration will be restricted to a single-bed system for simplicity sake.

The P–T–X diagram on $\ln P$ vs. $-1/T$ coordinates (where X is the amount of adsorbate adsorbed by the adsorbent at equilibrium conditions, kg adsorbate/kg adsorbent), is a convenient way to describe and model the thermodynamic cycle of an AD desalinator. Theoretically the cycle consists of two isosters and two isobars, as shown in Fig. 2.

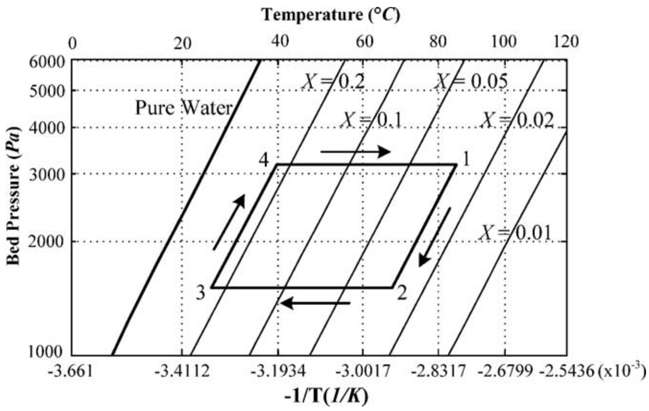

Fig. 2 – *P–T–X* diagram of the cyclic steady-state condition of the bed cycle. See text for a description of each process.