



Performance estimation of adsorption cooling cycle with sorption hysteresis



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HIGHLIGHTS

- The thermodynamic adsorption cooling cycle with hysteresis included is identified.
- The impact of sorption hysteresis on adsorption cycle performance is investigated.
- Over-estimation of cycle COP increases as the extent of hysteresis increases.

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ABSTRACT

Sorption hysteresis is the phenomenon where the adsorption and desorption isotherms for an adsorbate-adsorbent pair do not correspond. Despite such hysteresis being present for some common adsorbate-adsorbent pairs used in adsorption-based cooling systems, to date few previous studies take this into consideration when presenting the sorption (cooling) cycles and estimating their performances. This report addresses this deficiency by identifying the cycle on P-T diagram and developing a simulation model. We first provide the sorption characteristics of a silica gel/water pair that demonstrates sorption hysteresis. These sorption characteristics are then used with a newly developed equilibrium model to facilitate a comparison of the ideal cycle coefficient of performance (COP) with and without hysteresis for a range of operating conditions. Results show the cycle COP is over-estimated by around 14% when sorption hysteresis is ignored for the silica gel/water system. It is also shown that this over-estimation increases as the extent of hysteresis increases. The results suggest that, when it exists to any significant extent, sorption hysteresis should be accounted for when seeking to predict the performance of adsorption-based cooling systems.

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1. Introduction

The need to replace chlorofluorocarbons (CFCs) in vapour-compression refrigeration cycles has led to increasing interest in adsorption-based refrigeration or cooling cycles. Such cycles have a number of advantages [1–3], including: (1) they can be powered by heat sources ranging from 50 °C to 500 °C without corrosion issues arising; (2) they can be used where significant vibration is present such as, for example, on fishing boats and locomotives; and (3) there are fewer moving parts and, hence, lower maintenance costs.

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The variation of the amount of working fluid adsorbed, X , on the adsorbent with increasing pressure, P , at a fixed temperature, T , is termed as an adsorption isotherm, whilst that obtained with decreasing pressure at the same temperature is its matching desorption isotherm. Such sorption isotherm pairs are central to evaluating the performance of adsorption-based refrigeration systems. For example, an activated carbon/methanol working pair that is commonly used for adsorption-based refrigeration/ice making [4,5]. In such adsorbent/adsorbate working pair, the adsorption and desorption isotherms are essentially the same. However, this is not the case for the silica-gel/water working pair. The difference observed in adsorption isotherm and desorption isotherm is the so-called sorption hysteresis phenomenon [6,7]. Silica-gel/water is a common pair with sorption hysteresis while activated carbon/methanol is a pair without sorption hysteresis. In other words, for some range of pressures, the amount of water taken up by the silica with increasing pressure is less than that as pressure is

Nomenclature

K_0	pre-exponential constant (dimensionless)
C	specific heat (kJ/kg K)
P	pressure (Pa)
m	Mass (kg)
X	amount adsorbed by the adsorbent (dry mass) (kg/kg)
Q_{st}	isosteric heat of adsorption (kJ/kg)
r_p	pore radius (nm)
T	temperature (K)
R	gas constant (kJ/kg K)

<i>Subscripts</i>	
<i>ads</i>	adsorption
<i>bed</i>	adsorption bed or desorption bed
<i>cw</i>	cooling water
<i>cond</i>	condenser
<i>hw</i>	hot water
<i>evap</i>	evaporator
<i>des</i>	desorption
<i>w</i>	water
<i>sg</i>	silica gel

decreased. The reasons of the hysteresis phenomenon have been studied extensively [8–10]. Despite the existence of such hysteresis for some working pairs like the silica-gel/water, none of the previous studies of adsorption-based cooling systems (for example [11–17]), have considered the hysteresis when seeking to predict system performance, namely, all pairs were treated as sorption hysteresis free or at least, hysteresis were not considered separately in desorption process.

In this paper, the thermodynamic sorption cycle (of a adsorbate/adsorbent working pair) with sorption hysteresis is identified and presented for the first time to illustrate the effect of sorption hysteresis in the (adsorption) cooling cycle. Meanwhile its impact on the cycle performance estimation is also investigated by comparing the COPs – coefficient of performance of the (adsorption cooling) cycle with and without considering the sorption hysteresis.

2. The cycle with sorption hysteresis

2.1. Adsorptive properties for the pairs with and without hysteresis

The adsorptive properties of a given adsorbent/adsorbate pair are normally known by experimentally measuring the pair's adsorption and desorption isotherms. For the pair without hysteresis the adsorption and the desorption isotherms are overlapped, as shown in Fig. 1b. These experimental isotherm data is then to be fitted into an isotherm model to be expressed for easy application. Dubinin Astakhov (DA) isotherm (e.g. [18,19]), Langmuir isotherm (e.g. [20]), and Toth isotherm (e.g. [21]) are some of the often used isotherm models. Taking Toth model as an example, which is found to be the best fit for silica gel and water pair.

The Toth model takes the form as [16]:

$$X = X_{\max} \frac{K_p}{[1 + (K_p)^t]^{1/t}} \quad (1a)$$

where the temperature dependent term K_p is:

$$K_p = \frac{K_0}{X_{\max}} \exp[\Delta H_{ads}/(RT)]P \quad (1b)$$

2.2. Cycle COP calculation for the pairs with and without hysteresis

An adsorption/desorption cycle can be illustrated in so-called P - T - X (pressure-temperature and concentration) thermodynamic diagram that actually represents the thermodynamic properties of the working pair. For a pair with no sorption hysteresis, a particular P and a particular T would give one X value in the P - T - X diagram. An adsorption cooling cycle using a working pair without sorption hysteresis, consists of the following processes, as shown in Fig. 1a and b [20], i.e. two isobaric and two isosteric processes.

However, if a adsorbent/adsorbate working pair had sorption hysteresis e.g. silica/water, its P - T - X (pressure-temperature and concentration) diagram would be different. Namely, for a set of given P and T values, there may be two X values depending on the system is in adsorption process or desorption process. In other words, there are two constant X lines with the same X value in T - P coordinates: one is for adsorption process and the other is for desorption process, as shown in Fig. 2a. In Fig. 2a, the blue coloured lines are the adsorption constant X lines and the green lines are desorption constant X lines. Similarly, for the pair with hysteresis (included), there would be two isotherms at same temperature if presented in P - X coordinates, as shown in Fig. 2b. Accordingly, when presenting the adsorption/desorption cycle or processes of the pair with sorption hysteresis on P - T - X or isotherm (P - X) diagrams, the cycle turns to 1-2'-3'-4-1, instead of 1-2-3-4, as shown in Fig. 2a and b.

The Coefficient of Performance (COP) of a sorption (cooling) cycle is defined as

$$COP = \frac{Q_{Evap}}{Q_{Heating(\text{bed})}} \quad (2)$$

The Q_{Evap} in Eq. (2) is the effective cooling in the evaporator which can be expressed as

$$Q_{Evap} = m(\Delta X)\Delta h_{fg} - mC(\Delta X)(T_{Cond} - T_{Evap}) \quad (3)$$

The $Q_{Heating(\text{bed})}$ in Eq. (2) is the total heating input in the cycle which can be expressed with and without hysteresis as:

$$Q_{Heating(\text{bed})} = Q_{1-2} + Q_{2-3} \quad (\text{without hysteresis}) \quad (4a)$$

$$Q_{Heating(\text{bed})} = Q_{1-2'} + Q_{2'-3'} \quad (\text{with hysteresis}) \quad (4b)$$

where

$$Q_{1-2} = (X_1 mC + mC') \cdot (T_2 - T_1) \quad (5a)$$

$$Q_{1-2'} = (X_1 mC + mC') \cdot (T_{2'} - T_1) \quad (5b)$$

$$Q_{2-3} = \left[mC' + \left(\frac{X_2 + X_3}{2} \right) mC \right] \cdot (T_3 - T_2) + (X_2 - X_3) \cdot mQ_{des} \quad (6a)$$

$$Q_{2'-3'} = \left[mC' + \left(\frac{X_{2'} + X_{3'}}{2} \right) mC \right] \cdot (T_{3'} - T_{2'}) + (X_{2'} - X_{3'}) \cdot mQ_{des} \quad (6b)$$

When using above equations (model) to estimate the COP of an adsorption cooling cycle, the key point to be noted is that all X s with no-dash subscript (i.e. X_1 , X_2 , X_3 and X_4) should be calculated using desorption isotherms while all X s with dash subscript (i.e. $X_{1'}$, $X_{2'}$, $X_{3'}$ and $X_{4'}$) should be calculated using adsorption isotherms.

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