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Thermodynamic limits to thermal regeneration in adsorption cooling cycles

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ABSTRACT

Energy and exergy models for ideal adsorption cycles with isothermal beds and no mass recovery are developed to predict the limits to COP enhancement using thermal regeneration. The models are applied to compare the performance of zeolite–water and silica gel–water adsorbent–refrigerant pairs over a range of maximum bed temperatures. The thermodynamic consistencies of several alternate adsorption property assumptions are quantified. Differences in adsorption characteristics between zeolite–water and silica gel–water result in a significantly larger potential to enhance COP by implementing thermal regeneration for zeolite–water. Based on COP, the zeolite–water pair is preferred when both thermal regeneration and a high temperature thermal energy source (>150 °C) are used, while the silica gel–water pair is preferred when thermal regeneration is not used and/or a low temperature thermal energy source (<100 °C) is used.

Limites thermodynamiques à la régénération thermique dans les cycles de refroidissement à adsorption

Mots clés : Système à adsorption ; Zéolite ; Eau ; Modélisation ; Énergie ; Exergie ; Coefficient de performance (COP)

1. Introduction

Air-conditioning represents a large and/or rapidly growing part of the total energy demand in many countries (e.g., IEA, 2002; Papadopoulos et al., 2003). The negative economic and environmental consequences associated with conventional cooling technologies are well documented (e.g., IEA, 2002; Papadopoulos et al., 2003; Calm and Didion, 1998; Meunier, 2001; Calm, 2002). Adsorption cooling cycles can potentially reduce many of these negative consequences, since the primary energy input can be waste heat or solar thermal energy and environmentally benign adsorbent–refrigerant pairs such as natural zeolite–water can be used (Meunier, 2001; Dieng and Wang, 2001). Many reviews of this technology exist

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Nomenclature

c	specific heat of incompressible substance ($kJ\,kg^{-1}\,K^{-1}$)
c_p	ideal gas specific heat at constant pressure ($kJ\,kg^{-1}\,K^{-1}$)
e	exergy transfer via heat transfer per unit mass of adsorbent ($kJ\,kg^{-1}$)
e_D	exergy destroyed per unit mass of adsorbent ($kJ\,kg^{-1}$)
e_L	exergy lost per unit mass of adsorbent ($kJ\,kg^{-1}$)
h	enthalpy per unit mass of refrigerant ($kJ\,kg^{-1}$)
Δh_{ads}	differential enthalpy in adsorbed phase ($kJ\,kg^{-1}$)
M	molecular weight of refrigerant ($kg\,kmol^{-1}$)
m	mass (kg)
n	moles (kmol)
P	pressure (kPa)
R	heat capacity ratio of bed shell material and heat transfer fluid inside bed to adsorbent
q	heat transfer per unit mass of adsorbent ($kJ\,kg^{-1}$)
T	temperature (K)
u_{ads}	internal energy per unit mass of adsorbed refrigerant ($kJ\,kg^{-1}$)
$\bar{u}_{ads}$	partial molar internal energy of adsorbed refrigerant ($kJ\,kmol^{-1}$)
X	adsorption capacity (kg_{ads}/kg_{α})
y	exergy ratio: exergy normalized by fuel exergy (dimensionless)

Greek symbols

ε	exergetic cycle efficiency (%)
ψ	flow exergy per unit mass of refrigerant ($kJ\,kg^{-1}$)

Subscripts

α	adsorbent
ads	adsorbed phase or adsorption process
cold	cold thermal energy reservoir
cond	condenser
D	destroyed
dsh	desuperheater
evap	evaporator
F	fuel
hot	hot thermal energy reservoir
intra	intra-pair heat transfer
l	liquid
L	loss
o	environment
P	product
sat	saturation
sh	superheater
td	throttling device
tot	total
v	vapor (saturated and/or ideal gas)

(Meunier, 2001; Dieng and Wang, 2001; Sumathy et al., 2003; Critoph and Zhong, 2005; Lambert and Jones, 2005).

A potential barrier to commercialization of such a system is large collector costs (Baker and Kaftanoğlu, 2007a). Collector costs can be reduced by increasing the adsorption cycle's COP or decreasing the operating temperature of the collector (which both increases the collector's efficiency and allows less expensive collectors to be used). One method to increase the adsorption cycle's COP is through thermal regeneration (Lambert and Jones, 2005; Chua et al., 2001; Meunier et al., 1997; Wang, 2001; Ng et al., 2006). The maximum cycle temperature, and therefore collector temperature, is impacted by the choice of adsorbent–refrigerant pair (Restuccia and Cacciola, 1999). For example, using a silica gel–water pair instead of zeolite–water can result in lower maximum temperatures (Baker and Kaftanoğlu, 2007a; Chua et al., 2001; Wang et al., 2005). Several studies related to exergy and irreversibility have been performed on adsorption cycles (Meunier et al., 1997; Gui and Wang, 2001; Pons, 1997; Chua et al., 1998; Sorin et al., 2002; Okunev and Safonov, 2006). However, no previous research was identified that addressed the following issues: (1) the development and application of energy and exergy models to quantify the theoretical limits to thermal regeneration in an adsorption cycle with isothermal beds and no mass recovery; (2) how this limit to thermal regeneration is impacted by the adsorbent–refrigerant pair choice; and, (3) the extent to which adsorption property data and assumptions impact a model's ability to satisfy cycle energy and exergy balances. The objectives for the present research are therefore to address these three issues.

2. Thermodynamic models of ideal adsorption cycles

The adsorption cycle is modeled as receiving a hot *fuel* heat transfer q_F from a thermal energy reservoir (TER) at temperature T_{hot} and a cold *product* heat transfer q_P from a TER at temperature T_{cold}, and rejecting a *loss* heat transfer q_L to the environment at temperature T_o. In addition to quantifying the energy performance of the cycle in terms of COP, the exergetic performance is quantified using an exergetic efficiency (ε) defined as

$$\varepsilon = \frac{\text{Product Exergy}}{\text{Fuel Exergy}} = y_P = 1 - \sum_{\text{Losses}} y_L - \sum_{\text{Destroyed}} y_D \tag{1}$$

where y is an exergy ratio obtained by normalizing an exergy value (e) with respect to the fuel exergy (e.g., $y_P \equiv e_P/e_F$) (Tsatsaronis, 1999). The exergy loss and destruction ratios (y_L and y_D) are equivalent to the entropy generation numbers applied to adsorption cycles by Meunier et al. (1997).

Three adsorption cycles representing three limiting cases are considered: simple cycle, regenerative cycle, and reversible cycle. The simple cycle has no thermal regeneration. The regenerative cycle has the maximum thermal regeneration between isothermal adsorbent beds but no thermal regeneration elsewhere in the cycle. The reversible cycle is both internally and externally reversible.