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Performance simulation of multi-bed silica gel-water adsorption chillers☆

Xiaolin Wang [a,*], Zhilong He [b], Hui Tong Chua [c]

[a] School of Engineering & ICT, University of Tasmania, Private Bag 65, Hobart, TAS 7001, Australia
[b] School of Energy and Power Engineering, Xi'an Jiaotong University, 28 Xianning West Road, Xi'an 710049, China
[c] School of Mechanical and Chemical Engineering, The University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia

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ABSTRACT

Adsorption chiller technology is one of effective means to convert waste thermal energy into cooling, which substantially improves energy efficiency and lowers environmental pollution. This article develops an improved lumped-parameter model for multi-bed silica gel-water adsorption chillers. It is validated by experimental results stemming from a four-bed silica gel-water adsorption chiller at various operating conditions. It is found that the performance predictions from this model compare favourably with experimental results. At all tested conditions and over a wide range of cycle times, the cooling capacity and COP can be predicted to within 10% and 12%, respectively.

Simulation de la performance de refroidisseurs à adsorption de gel de silice-eau à lits multiples

Mots clés : Refroidisseur à adsorption ; Refroidissement ; Gel de silice ; Performance ; Simulation

1. Introduction

In the past three decades, silica gel-water adsorption chillers have been proven to be an economically viable and environmentally friendly technology that can effectively convert waste thermal energy to useful cooling (Boelman et al., 1995; Chua et al., 1999; Saha et al., 2001, 2003a, 2003b, 2007; Chua et al., 2004; Ng et al., 2006a, 2006b). In the commercial market, this genre of adsorption chillers can be driven by any conceivable form of thermal energy with temperatures above 80 °C.

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* *Corresponding author*. Tel.: +61 3 62262133; fax: +61 3 62267247.
E-mail address: Xiaolin.wang@utas.edu.au (X. Wang).

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Nomenclature

A	heat transfer area, m^2
COP	coefficient of performance
c_v	specific heat capacity, J $(kg\ K)^{-1}$
D_{so}	pre-exponent constant, $m^2\ s^{-1}$
E_a	activation energy of surface diffusion, kJ kg^{-1}
h	enthalpy, J kg^{-1}
$\hbar$	heat transfer coefficient, W $(m^2\ K)^{-1}$
k	thermal conductivity, W $(m\ K)^{-1}$
L	Length of pipes, m
M	Mass, kg
N	number of discrete elements in the heat exchanging tubes of the beds
N_1	number of discrete elements in the heat exchanging tubes of the evaporator
N_2	number of discrete elements in the heat exchanging tubes of the condenser
N_{tube}	number of discrete elements in the connecting pipes
$NA_{cross,tube}$	The annulus cross section area of the tube, m^2
P	pressure, Pa
q	fraction of refrigerant as adsorbed by the adsorbent, kg per kg dry adsorbent
q^*	fraction of refrigerant which can be adsorbed by the adsorbent under saturation condition, kg per kg dry adsorbent
Q_{evap}	cycle average cooling capacity, W
R	universal gas constant, J $(mol\ K)^{-1}$
R_p	average radius of silica gel, m
t	time, s
t_{cycle}	cycle time, s
T	temperature, °C
$U_{chilled}$	heat transfer coefficient of the evaporator, W $(m^2\ K)^{-1}$
U_{cond}	heat transfer coefficient of the condenser, W $(m^2\ K)^{-1}$
U_c	heat transfer coefficient of the adsorber, W $(m^2\ K)^{-1}$
U_h	heat transfer coefficient of the desorber, W $(m^2\ K)^{-1}$
V	internal volume of heat exchanger tubes, m^3
$\dot{m}$	flow rate, kg s^{-1}
ΔH_{ads}	isosteric heat of adsorption, J kg^{-1}
δ	flag that governs connecting pipe transients
ζ	flag that governs adsorber transients
γ	flag that governs evaporator transients
θ	flag that governs condenser transient
ρ	density, kg m^{-}

Superscripts/Subscripts

air	air
ads	adsorption
bed	adsorption or desorption bed
chilled	chilled water
cond	condenser or condenser cooling water
cool	cooling water or bed cooling water
cycle	cycle
evap	evaporator or chilled water
f	fluid (liquid water)
g	gaseous water
hot	hot water or heating
Hex	heat exchanger tube-fin assembly
i	adsorber
in	inlet
j	desorber
k	discrete element
m	metal tube or water in the connecting pipes
pm,hot	metal tube between desorber outlet and system outlet
pm,cool	metal tube between adsorber outlet and system outlet
out	outlet
p-a	pre-cooling
p-h	pre-heating
rec	recovery
ref	reference
rej	rejected energy
sat	saturated
sg	silica gel

Researchers further extend the chiller application in low grade heat sources with temperature as low as 55 °C (Saha et al., 1995; Chua et al., 2001) by adopting a multi-bed & multi-stage design. The main advantages of the silica gel-water adsorption chillers are that (i) they lack moving parts and have no vibration, which gives rise to quiet operation and low maintenance; (ii) the refrigerant is water which is environmentally benign and (iii) the recovery of waste heat which otherwise would have been purged into environment, and thereby maximizing energy utilization efficiency. Furthermore in comparison to absorption chillers, they have no problem with corrosion and crystallization, which makes their construction much simple.

However the adsorption chiller certainly does not enjoy even a fraction of the extent of deployment as does its vapour compression counterpart. Its major militating factors are low Coefficient of Performance (COP), large footprint and mass, lack of continuity of operation. Over the past 30 years, extensive efforts have been devoted to improve the adsorption chiller performance. Various technologies have been developed. These include cascading cycle (Douss et al., 1998), thermal wave (Critoph, 1992), combined heat and mass recovery (Qu et al., 2001; Wang, 2001), mass recovery (Akahira et al., 2004) and passive heat recovery (Wang and Chua, 2007a, 2007b). GBU mbH and Mayekawa Manufacturing Co. Ltd are currently applying the water-circulation heat recovery technology between the adsorber and desorber during switching in their commercial chillers. All these technologies significantly improve the conversion efficiency for a standard two bed adsorption chiller.

Furthermore, in order to maximizing enthalpy extraction from the waste heat, Saha et al. (1995) studied a multi-stage silica gel-water adsorption chiller which could be operated