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Simulation of operating characteristics of the silica gel–water adsorption chiller powered by solar energy

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Abstract

A lumped parameter model of a silica gel–water adsorption chiller driven by solar energy was introduced for the operating characteristics investigation. Matlab–Simulink, as a high-performance computing and programming tool, was used to simulate the operating characteristics of the chiller. Effects of the hot water tank capacity, the cycle time and the initial hot water temperature on the performance of the chiller were analyzed when the chiller was driven by a stable heat source and solar energy respectively. The simulation results indicated that when the chiller was driven by solar energy, the open circulation of the hot water with a short cycle time and the closed circulation of hot water with a longer cycle time were better. A proposal was also provided for the chiller driven by solar energy to work under the optimum working conditions, such as hot water circulation mode, cycle time and initial temperature.

Keywords: Adsorption refrigeration; Simulink; Silica gel–water; Solar energy; Simulation

1. Introduction

As a good opportunity to replace the CFCs or HCFCs refrigeration, the adsorption refrigeration has been paid considerable attentions. Compared to two-stage absorption refrigeration, adsorption refrigeration has no distillation (ammonia–water system), corrosion or crystallization (lithium bromide–water system) problem, lower equipment cost and more effective when low grade thermal energy, such as solar energy and the waste heat from an engine, acts as the driving heat source.

In the past two decades, a large number of researches about the adsorption refrigeration technology have been done, which include the adsorption mechanism (Wang, 2001), the thermodynamic analysis of various adsorption refrigeration cycles (Sumathy et al., 2003), simulations of adsorption refrigerator (Saha et al., 1995; Chua et al., 1999) and heat pump and applications of adsorption systems in solar energy and waste heat utilization (Fan et al., 2007). As one of the most influential parameters on both refrigerating capacity and COP, the cycle time also has been further studied. Both the experimental analysis by Boelman et al. (1995) and the simulation models by Saha et al. (1995) and Chua et al. (1999) showed that there exists an optimum cycle time for the refrigerating capacity, but the COP increases monotonically with increase of the cycle time at a certain period of time. Alam et al. (2000, 2003) investigated effects of the heat exchanger design parameters on the switching frequency, and the results showed that the optimum switching frequency is very sensitive to the heat exchanger's design parameters, and increases with the increase of adsorbent number of transfer unit (NTU), heat exchanger thickness ratio (Hr) and with the decrease of bed Biot number (Bi), the heat exchanger aspect ratio (Ar). Miyazaki et al. (2009) proposed a new cycle time allocation not only to improve the cooling

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Nomenclature

A	parameter of adsorption equation/area (m^2)
B	parameter of adsorption equation
c	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
COP	coefficient of performance
D_{so}	pre-exponential term ($m^2\ s^{-1}$)
E_a	activation energy ($J\ kg^{-1}$)
J	every day solar radiation ($kJ\ m^{-2}$)
KA	performance coefficient of heat exchanger ($W\ K^{-1}$)
L	latent heat of vaporization ($kJ\ kg^{-1}$)
M	mass (kg)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
P	pressure (Pa)
q	heating power (kW)
Q	heat power (kW)
R	gas constant ($J\ kg^{-1}\ K^{-1}$)
R_p	adsorbent particle radius (m)
T	temperature (K)
x	adsorption capacity ($kg\ kg^{-1}$)
ΔH	isosteric heat of adsorption ($kJ\ kg^{-1}$)
τ	time (s)
δ	flag functions
η	the average collection efficiency of solar collectors

Subscript

a	adsorbent
ad	adsorber
ads	adsorption
al	aluminum
ave	average
b	desorber/adsorber
c	condenser
chill	chilled water
cool	cooling water
collectors	collectors
cu	cuprum
des	desorption
e	evaporator
h	heat, hot
hwt	hot water tank
in	inlet
out	outlet
ref	refrigeration
s	silica gel, saturation
w	water
wv	water vapor

capacity and the COP, but also to contribute in the reduction of delivered chilled water fluctuations.

As we known, an adsorption chiller is also sensitive to the changes of heat source. The instability or intermittence of heat source is an unavoidable problem when the adsorption refrigeration is applied to waste heat recovery or solar energy utilization. Therefore, it is necessary to study the operating characteristics of an adsorption refrigeration system and then reduce the adverse effect of unstable heat source on adsorption refrigeration system, while the adsorption refrigeration is applied to the utilization of solar energy or waste heat from an engine. Wang et al. (2005a,b) have developed a novel silica gel–water adsorption chiller and Zhai et al. (2008) analyzed its operating characteristics when powered by solar energy. The results indicated that the longer cycle time is advantageous to the system when the heat source temperature is the lower (about 65 °C), otherwise the shorter cycle time should be adopted. Di et al. (2007) theoretically and experimentally investigated on the performance and characteristics of such chiller driven by solar energy and gave the control strategies of the adsorption chiller. The results showed that the COP is significantly influenced by the variation rates of the heat source temperatures. However, they did not consider effects of the initial hot water temperature and the hot water tank capacity on the performance of the chiller.

From this context, based on the model of Wang et al. (2005a), a mathematical model to simulate the adsorption chiller powered by solar energy was introduced. The performance of this chiller is investigated when it operates with different initial temperatures, different volume of hot water tank and different cycle times. These results are compared with those of the chiller powered by a stable heat source, and then the operating strategies which optimize operating performance of the chiller are proposed.

2. Adsorption chiller

Fig. 1 shows the structure of the silica gel–water adsorption chiller which is developed by Wang et al. (2005a,b) at Shanghai Jiao Tong University. This silica gel–water adsorption chiller is composed of three working vacuum chambers, which include left, right desorption/adsorption working chambers and one heat pipe working vacuum chamber as the evaporator (indicated in Fig. 1). Each of desorption/adsorption working chambers comprises one condenser, one adsorber and one evaporator (including half water-evaporating surface of the heat pipe evaporator). The operating mode and the structure in detail are described in literatures (Wang et al., 2005a). In order to simplify the calculation, the operating mode without heat and mass recovery was adopted in this study.

3. Mathematical model

In adsorber of the adsorption chiller showed in Fig. 1, the radius of the granular silica gel is 0.5–0.75 mm and the vapor flow speed is low except in the beginning of the