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Study of various adsorbent–refrigerant pairs for the application of solar driven adsorption cooling in tropical climates

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HIGHLIGHTS

- Examines the performance of solar driven adsorption chillers for tropical regions.
- Three different adsorbent–refrigerant pairs have been studied.
- Results are useful in selecting suitable adsorbent–refrigerant pairs.

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ABSTRACT

This article presents analytical investigation results on the performance of solar powered adsorption cooling systems for Malaysia and similar tropical regions. The studied adsorbent–refrigerant pairs are silica gel-water, activated carbon fiber-ethanol and activated carbon-methanol. A computer simulation program has been developed for modeling and performance evaluation for the solar driven adsorption cooling cycle using the meteorological data of Kuala Lumpur, Malaysia The simulation is based on the experimentally confirmed adsorption isotherms, kinetics and isosteric heat of the adsorption data for the respective adsorbent–refrigerant pairs. The optimum cooling capacity and coefficient of performance (COP) of the different adsorbent–refrigerant pairs varying adsorption–desorption cycle time, regeneration temperature and chilled water inlet temperature are calculated and compared.

1. Introduction

Thermally powered sorption cooling systems have attracted much attention as they appear to be promising from the view point of greenhouse gas emissions and ozone layer depletion problems [1]. Chlorofluorocarbons (CFCs) and Hydro-chlorofluorocarbons (HCFCs) have been considered as the major contributors to the environmental hazard. Thermally driven adsorption based chillers have zero ozone depletion potential due to the use of natural and/or alternative refrigerants like water, ammonia, methanol, ethanol, etc. As solar energy or low grade waste heat can be effectively utilized to run these systems, it has the potential to reduce the peak load demand of electricity and the emission of greenhouse gases as well. The other advantages of adsorption refrigeration systems are that they are free of vibrations as they do not have any moving parts, simple control and lower operation cost. Thermally powered adsorption cooling cycle could be operated in both partial vacuum and pressurized conditions. The adsorbent–refrigerant pairs working at sub-atmospheric conditions are silica gel-water [1,2], zeolite-water [3,4], activated carbon fiber-ethanol [5,6], activated carbon-methanol [7,8], etc.

Solar adsorption refrigeration system seems to be a promising alternative refrigeration device since cooling load of buildings is roughly in phase with solar energy availability. During the past decades much research has been performed on solar adsorption refrigeration. Table 1 lists solar driven adsorption refrigeration systems using various adsorbent–refrigerant pairs.

The present study introduces a comparison of solar driven adsorption cooling systems using the meteorological data of Kuala Lumpur. A cycle simulation computer program has been developed

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Nomenclature

Symbols

α_0	coefficient in Eq. (1) [kg (kg of dry adsorbent)$^{-1}$]
α_1	coefficient in Eq. (1) [kg (kg of dry adsorbent, K)$^{-1}$]
α_2	coefficient in Eq. (1) [kg (kg of dry adsorbent, K^2)$^{-1}$]
α_3	coefficient in Eq. (1) [kg (kg of dry adsorbent, K^3)$^{-1}$]
β_0	coefficient in Eq. (1) [−]
β_1	coefficient in Eq. (1) [K^{-1}]
β_2	coefficient in Eq. (1) [K^{-2}]
β_3	coefficient in Eq. (1) [K^{-3}]
A	area [m^2]
A_c	collector area [m^2]
COP	coefficient of performance [−]
C_p	specific heat capacity [J/kg-K]
D_s	surface diffusion coefficient [m^2/s]
D_{so}	pre-exponential constant [m^2/s]
E_a	activation energy [J/kg]
h	enthalpy [J/kg]
M	mass [kg]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
P_s	saturation pressure [Pa]
Q	power [W]
Q_u	useful energy gain from collector [W]
R	gas constant [J/kg-K]
R_p	adsorbent fiber radius [m]
T	temperature [°C or K]
τ	time [s]
U	overall heat transfer coefficient [W/m^2-K]
U_L	overall heat transfer coefficient of collector to ambient [W/m^2-K]
F_R	collector heat removal factor [−]
I	incident solar radiation [W/m^2]
$\tau\alpha$	effective transmittance-absorptance product [−]
E	characteristic energy [J/kg]
n	heterogeneity constant [−]
x	instantaneous uptake [kg/kg]
x^*	equilibrium uptake [kg/kg]
x_0	limiting adsorption uptake [kg/kg]
Δh_{st}	isosteric heat of adsorption [J/kg]
η	efficiency [−]

Subscripts

sg	silica gel
f	liquid phase
a	adsorbent
g	gaseous phase
in	inlet
out	outlet
w	water
bed	sorption heat exchanger (adsorber/desorber)
col	collector
amb	ambient

Superscripts

ref	refrigerant

to analyze cooling capacity and COP by varying adsorption/desorption cycle time, regeneration temperature and chilled water inlet temperature. Performance data of silica gel-water, activated carbon fiber-ethanol and activated carbon-methanol based adsorption systems have been presented and compared. The results obtained from this analysis will be useful in selecting a suitable adsorbent–refrigerant pair for adsorption cooling in tropical climates.

2. Working principle of the solar adsorption chiller

In the present study, a two bed solar powered adsorption cooling cycle has been studied. The schematic diagram of the adsorption cycle is shown in Fig. 1. The chiller is composed of four heat exchangers namely two adsorber/desorber heat exchangers, an evaporator and a condenser. Four refrigerant valves are used for the operation four pre-determined processes namely, adsorption, pre-heating, desorption and pre-cooling. As can be seen from Fig. 1, refrigerant evaporates from the evaporator and adsorbed by the adsorber bed through refrigerant valve V4. At the same time desorbed refrigerant goes to the condenser through refrigerant valve V2 which is known as the desorption-condensation process. The desorber bed is powered by solar thermal heat which is the only heat source of the studied system. The details of the working principle of adsorption chiller have been described in detail elsewhere [1].

3. Adsorbent-refrigerant pair

In the present study, three different adsorbent–refrigerant pairs have been selected and these are silica gel-water, activated carbon fiber (ACF)-ethanol and activated carbon (AC)-methanol. The porous properties of silica gel, ACF and AC are listed in Table 2. It is evident from Table 2 that ACF possesses largest surface area which is followed by activated carbon. ACF also has higher adsorption capacity than the other two studied adsorbents. On the other hand, silica gel has higher apparent density compared to ACF and AC, which indicates that it is easier to pack relatively larger amount of silica gel into the adsorbent bed of the silica gel-water based adsorption chiller.

4. Mathematical modeling

4.1. Adsorption kinetics

Adsorption rates of silica gel-water, ACF-ethanol and AC-methanol pairs are estimated from the linear driving force equation.

$$\frac{dx}{d\tau} = 15\frac{D_{so}\exp\left(-\frac{E_a}{RT}\right)}{R_p^2}(x^* - x) \tag{1}$$

The numerical values of D_{so} and E_a for silica gel water [1], ACF-ethanol [5] and AC-methanol [26] are evaluated experimentally.

4.2. Adsorption isotherms

For silica gel-water system, the S–B–K isotherm model [27], which is expressed by Eq. (2), is used to estimate the equilibrium uptake.