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Performance evaluation and determination of minimum desorption temperature of a two-stage air cooled silica gel/water adsorption system

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HIGHLIGHTS

- Numerical and thermodynamic study of two-stage air cooled adsorption chiller cum desalination system is carried out.
- Effect of assorted heat source temperatures on optimum cycle time is investigated.
- Realistic minimum desorption temperature for the present prototype is predicted from the simulation results.
- Theoretical limit for minimum desorption temperature is derived from thermodynamic principles.
- Thermodynamic analysis depicts the presence of optimal inter-stage pressure for the system.

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ABSTRACT

This paper presents an in-depth numerical and thermodynamic study of a two-stage, 2-bed silica gel/water adsorption system for simultaneous generation of cooling power and potable water. The system is air cooled where the ambient temperature remains constant at 36 °C. The first part of this paper investigates the effect of cycle time, chilled water inlet and heat source temperature on system performance *viz.* specific cooling capacity (SCC), specific daily water production (SDWP) and coefficient of performance (COP). A significant outcome of this study is to show that decrease in heat source temperature not only reduces the specific throughput but also increases the optimum cycle time, whereas COP is relatively insensitive to such alterations. The second part of this paper discusses the estimation of the minimum desorption temperature from the simulated system throughput results as well as from fundamental thermodynamic analysis of a two-stage adsorption cycle. This thermodynamic analysis provides a theoretical limit for minimum desorption temperature and optimal inter-stage pressure for a two-stage adsorption cycle.

1. Introduction

Solid-sorption has been employed for gas storage [1–4], cooling/refrigeration [5–9], desalination [10–15] as well as energy storage [16–21] applications. These systems utilize the cyclical adsorption/desorption of vapor (adsorbate) onto the surface of porous solids (adsorbent) and are driven by an external temperature or pressure swing. For refrigeration/cooling application, several adsorbents like silica gel [22–24] and its composite with $CaCl_2$ [25] and LiCl + LiBr [26], zeolites [27–29], activated carbons [8,9,30–32] and very recently MOFs [33–35] have been explored. Natural refrigerants like water, ethanol and methanol are frequently used with these adsorbents. Present paper elucidates a thermally driven (temperature swing) silica gel/water based adsorption chiller which not only generates cooling but also produces potable water as by-product. The advantages of this system over mechanical vapor compression chillers are: (a) mitigation of carbon emission by decreasing the consumption of fossil fuel necessary for cooling applications; (b) insignificant global warming and no ozone depletion potential due to the use of water as refrigerant; (c) production of dual-effect makes it suitable for poly-generation systems [36]. Silica gel/water pair has been extensively studied in literature to study the adsorption characteristics [37–39] as well as investigate heat and mass transfer through adsorber bed [40–42]. This adsorption pair has been successfully deployed in several standalone cooling and desalination

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Nomenclature

A	area [m^2]
C_{sf}	Rohsenhow coefficient [–]
c_p	specific heat capacity [kJ kg^{-1} K^{-1}]
D_{so}	diffusivity [m^2 s^{-1}]
d	diameter [m]
E_a	activation energy [kJ kg^{-1}]
g	acceleration due to gravity [m s^{-2}]
$\hbar$	heat transfer coefficient [kW m^{-2} K^{-1}]
h	enthalpy [kJ kg^{-1}]
K_o	Tóth isotherm coefficient [kPa^{-1}]
k	thermal conductivity kW m^{-1}K^{-1}
L	length [m]
M	mass [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
N_{cyc}	number of cycles per day [–]
Pr	Prandtl number [–]
p	pressure [kPa]
Q	thermal energy [kJ]
$\dot{Q}$	thermal power [kW]
q''	heat flux [kW m^{-2}]
R	characteristics gas constant [kJ kg^{-1} K^{-1}]
R_p	radius of silica gel particle [m]
Re	Reynolds number [–]
T	temperature [°C]
t	time [s]
U	overall heat transfer coefficient [kW m^{-2} K^{-1}]
x	Tóth isotherm constant [–]

Greek symbols

ε	error tolerance [kg s^{-1}]
ϕ,ϕ^*	instantaneous uptake, equilibrium uptake [kg kg^{-1}]
ϕ_m	monolayer saturation uptake [kg kg^{-1}]
λ	switching parameter [–]
μ	viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
τ	time constant [s]
ψ	area ratio [–]

Subscripts

ads	adsorption
atm	atmospheric
bed	adsorber bed
ch	chilled water
cond	condenser
cw	cold water
cyc	cycle
des	desorption
evap	evaporator
fg	vaporization
hw	hot water
i	inner
in	inlet/input
int	inter-stage
min	minimum
o	outer
opt	optimal
out	outlet
res	residual
sat	saturated condition
sg	silica gel
tot	total
v	water vapor
w	liquid water

Superscripts

I	stage-1 adsorber
II	stage-2 adsorber

systems [10–12,22–24] besides few hybrid systems [43–45]; utilizing either solar or waste heat as the energy source. However, it must be mentioned that all these studies focus on single-stage operation with cooling towers for heat rejection. Even few multi-stage adsorption chillers discussed in literature [46,47] use wet cooling.

Adsorption system chosen for the present investigation employs air cooling. This avoids the loss of precious heat exchange grade make-up water and also eliminates legionella problem faced by many cooling towers [48,49]. These advantages make air cooled adsorption system ideal for both arid and tropical places with only requirement being the availability of low-grade thermal energy either in the form of waste heat from industries or solar heat. Mitra et al. [50] numerically investigated the effect of cycle time and condenser temperature on the performance of an air cooled silica gel/water adsorption cooling cum desalination system. The simulation results illustrated the necessity of two-stage system for condenser temperature higher than 35 °C. This was followed by experimental studies of a two-stage air cooled laboratory prototype [51,52] wherein 2-,3-and 4-bed modes of operation with varying evaporator pressures were investigated. The air temperature in those studies was found to be 36 °C. The ineffectiveness of single-stage system for such high ambient temperature was revealed through a comparative study with two-stage operation [51]. Nonetheless, it is interesting to note that all these studies were performed for constant heat source temperature of 85 °C.

An important feature of adsorption system is its capability to recover low temperature thermal energy; hence, it is imperative to evaluate the system performance for assorted heat source temperatures. In none of the studies described above [50–52], the effect of heat source temperature on the system performance been evaluated. Furthermore, these studies do not discuss the role of inter-stage pressure on regeneration temperature for a two-stage adsorption chiller. The endeavor of this study is to bring forth these aspects through a detailed numerical analysis. The fundamental principles of modeling framework remain similar to our recent study [53]; however, unlike the previous study, present paper implements detailed heat transfer mechanisms for evaporation and condensation. The existence of varying optimum cycle time for a single-stage water cooled system driven by altering heat source qualities is experimentally investigated by Thu et al. [54]. Here, we investigate the presence of such phenomena for an air cooled two-stage adsorption cycle. The selected heat source temperature ranges between 65–85 °C and chilled water inlet temperature is varied between 11.5–24 °C. The system performance is investigated along with the optimal operating cycle times. Based on these characteristics, the realistic minimum desorption temperature for present system is also estimated; which indicates the minimum heat source temperature at which the prototype is functional. This is followed by an in-depth analysis to determine the thermodynamic limit of minimum desorption temperature for a two-stage adsorption cycle. During this analysis, the role of inter-stage pressure is also elucidated, contrary to prior arts [55,56] where it was assumed constant. To summarize, the objectives of this simulation study are: