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Simulation study of a two-stage adsorber system

Sourav Mitra, Pramod Kumar, Kandadai Srinivasan, Pradip Dutta*

Department of Mechanical Engineering, Indian Institute of Science, Bangalore, Karnataka 560012, India

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The present study simulates a two-stage silica gel + water adsorption desalination (AD) and chiller system. The adsorber system thermally compresses the low pressure steam generated in the evaporator to the condenser pressure in two stages. Unlike a standalone adsorption chiller unit which operates in a closed cycle the present system is an open cycle wherein the condensed desalinated water is not fed back to the evaporator. The mathematical relations formulated in the current study are based on conservation of mass and energy along with isotherm relation and kinetics for RD-type silica gel + water pair. Various constitutive relations for each component namely the evaporator, adsorber and condenser are integrated in the model. The dynamics of heat exchanger are modeled using LMTD method, and LDF model is used to predict the dynamic characteristic of the adsorber bed. The system performance indicators namely, specific cooling capacity (SCC), specific daily water production (SDWP) and coefficient of performance (COP) are used as objective functions to optimize the system. The novelty of the present work is in introduction of inter-stage pressure as a new parameter for optimizing the two-stage operation of AD chiller system.

1. Introduction

The ever decreasing fresh water availability and rising fuel costs have led to a thrust in research for unconventional and innovative methods of desalination. Further, the demand for space cooling and refrigeration is also on the rise especially in developing countries. The conventional systems for desalination like multi-stage flash (MSF), reverse osmosis (RO) and refrigeration cooling systems like vapor compression refrigeration system (VCRs) are either highly energy intensive or require high maintenance costs. Thus, there is a need for a system that not only tackles the dual needs of cooling and desalination but utilizes minimum electricity, and at the same time has low maintenance costs.

Silica gel + water adsorption desalination (AD) cum chiller running on low grade thermal energy (60–85 °C) seems to be a viable solution. The system consumes minimum electricity as it replaces the energy intensive mechanical compression process with thermal compression which predominantly requires only heat as input. Further, avoidance of moving parts during compression and absence of costly membranes for desalination, the system maintenance can be expected to be cheap. Ng et al. [1,2] have compared various refrigeration and desalination systems and have reported that AD systems offer one of the most cost effective and environment friendly solution due to significant reduction in consumption of high grade energy thereby reducing fuel cost and carbon emission. Extensive experimental and simulation studies have been performed to investigate the transient behavior of single-stage AD system in various configurations and operating conditions. Sami and Tribes [3] developed a lumped parameter model with single- and/or two-bed adsorber chiller having air cooled condenser and evaporator. They validated the model with experimental results obtained for AC35-R123 pair. Chua et al. [4] presented a lumped transient model for two-bed silica gel + water adsorber chiller where they analyzed the effect of cycle time and switching time on the system performance. Subsequently, an improved model was presented by Chua et al. [5] taking into account the geometry of the adsorber beds and thermal inertia of metal pipes. Miyazaki et al. [6] studied the 2-bed silica gel + water adsorber chillers and proposed a new operating cycle time to maximize its COP and minimize the fluctuations at evaporator. Studies were performed for two types of silica gel viz. RD-type and $CaCl_2$-in-silica gel type. Thu et al. [7] experimentally compared the performance of single-stage adsorption desalination system operating in 2-bed and 4-bed mode where they observed that the four-bed mode resulted in significantly higher desalinated water output. Further, it was observed that the 4-bed mode of operation has

* Corresponding author.
E-mail address: pradip@mecheng.iisc.ernet.in (P. Dutta).

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Nomenclature

A	area, m^2
c_p	specific heat capacity, kJ/kg K
h	enthalpy, kJ/kg
M	mass, kg
$\dot{m}$	mass flow rate, kg/s
$N_{cycle/day}$	no. of cycles per day
n_{bed}	no. of beds
P	pressure, kPa
Q	heat energy, kW
R_p	radius of silica gel particle, m
T	temperature, °C
t	time, s
U	overall heat transfer coefficient, kW/m^2 K

Greek symbols

ϕ	uptake

Subscripts

ads	adsorption
ch	chilled water
cond	condenser
cw	cold water
des	desorption
eff	effective
evap	evaporator
fg	vaporization
hw	hot water
i	in
in	input
o	out
s	silica gel
tot	total

Superscripts

I	stage-1 adsorber
II	stage-2 adsorber
cond	condenser
evap	evaporator

shorter optimum cycle time when compared to two-bed mode. An investigation to study the efficacy of evaporator–condenser heat recovery for water desalination was carried out by Thu et al. [8]. Their modeling study revealed a significant increase in desalination throughput which agreed well with the experimental results. Similar modeling studies were recently carried out by Thu et al. [9] where they reported a threefold increase in desalinated water throughput due to internal heat recovery, resulting in very low specific electricity consumption. Chang et al. [10] developed a single-stage 2-bed solar heat driven silica gel + water adsorption chiller wherein they achieved 9 kW of cooling power with 80 °C hot water at a COP of 0.37 and cooling capacity of 72 W/kg. Miyazaki and Akisawa [11] investigated the influence of heat exchanger parameters namely heat capacity and number of transfer unit (NTU) on the overall system performance of single-stage silica gel + water adsorption chiller. They found out that higher NTU and lower heat capacity of the heat exchanger are favorable for higher cooling capacity and COP. Thus, it can be observed that the literature on single-stage operation of AD chillers is quite abundant. However, the number of studies reported for multi-stage multi-bed adsorption systems are relatively scarce.

A multi-stage AD system is especially necessary when recovering very low temperature (<70 °C) heat and/or when the operating differential pressure between evaporator and condenser is high (~20 kPa). Saha et al. [12] computationally analyzed the operation of three-stage 2-bed silica gel + water adsorption chiller operating with 50 °C heat source where the system performance is studied for different silica gel mass and thermal conductance of the evaporator and condenser. However no studies were performed to study the effect of the inter-stage pressures. Saha et al. [13] have developed a solar/waste heat driven two-stage 2-bed adsorption chiller prototype and studied it experimentally system which produced 3.54 kW of cooling with 55 °C heat at a COP of 0.36. Later, Saha et al. [14] analytically investigated the performance of a dual-mode adsorber chiller which operates as three-stage 2-bed adsorption system operating with 50–60 °C heat source and as a single-stage 6-bed system with 65–90 °C heat source. The analysis depicted effective utilization of heat for large range of temperatures with COPs ranging from 0.20 to 0.45; however the operating condenser pressure was only 4.2 kPa. Khan et al. [15] recently studied the effect of thermal capacitance ratio, thermal conductance ratio and silica gel mass on the performance of a reheat two-stage silica gel + water adsorption chiller where they found that light weight sorption elements increase the performance of the chiller. They also observed that COP of the chiller is inversely proportional to the silica gel mass in the system.

In tropical areas such as India, it is inevitable for the condenser pressure of silica gel + water adsorber system to be as high as 12.2 kPa during summer. However, if the operating condenser pressure is raised further to about 20 kPa, there is an added benefit of easy pumping out the desalinated water to atmospheric pressure without the requirement of expensive low suction head pump. Furthermore, if solar energy is to drive such an AD chiller system, a source temperature higher than 85 °C is not preferable as it will require expensive collection devices such as evacuated tube solar collectors. From the above perspectives, the current work presents the simulation study of a proposed laboratory two-stage 4-bed/stage AD chiller system wherein the study focuses on the comparison of the performance of the AD chiller for various inter-stage pressures and cycle times with a condenser pressure of 20 kPa. It may be noted that the previous studies on multi-stage adsorption chiller [11–13] have not discussed the effect of inter-stage pressure on system performance and this paper introduces the new parameter for study and optimization of multi-stage adsorption systems.

2. The two-stage adsorption system

Fig. 1 shows the schematic of a laboratory two-stage AD system being developed with various design parameters as tabulated in Table 1. The system comprises of 4-beds in each stage. Brackish water enters the evaporator where it is flash evaporated at the low pressure P_{evap}. This steam now enters stage-1 adsorber beds wherein it is thermally compressed to the inter-stage pressure. The steam at this intermediate pressure enters the stage-2 adsorber beds via the distribution plenum 1, where it is further compressed to the condenser pressure P_{cond}. The inter-stage plenum 1 is necessary for damping any pressure fluctuations arising due to the differential desorption and adsorption rates of stage-1 and stage-2 respectively. The steam desorbed from stage-2 bed enters the condenser; it condenses and gets collected in a tank. This condensed desalinated water is then pumped out to the atmospheric pressure.