Energy Conversion and Management 126 (2016) 373–384

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Low grade heat driven adsorption system for cooling and power generation using advanced adsorbent materials

Fadhel Noraldeen Al-Mousawi *, Raya Al-Dadah, Saad Mahmoud

School of Mechanical Engineering, University of Birmingham, B15 2TT, United Kingdom

ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form 6 August 2016
Accepted 8 August 2016

Keywords:
Adsorption system
Cooling and power
AQSOA-Z02 (SAPO-34)
MIL101Cr

ABSTRACT

Globally there is abundance of low grade heat sources (around 150 °C) from renewables like solar energy or from industrial waste heat. The exploitation of such low grade heat sources will reduce fossil fuel consumption and CO_2 emissions. Adsorption technology offers the potential of using such low grade heat to generate cooling and power. In this work, the effect of using advanced adsorbent materials like AQSOA-Z02 (SAPO-34) zeolite and MIL101Cr Metal Organic Framework (MOF) at various operating conditions on power and cooling performance compared to that of commonly used silica-gel was investigated using water as refrigerant. A mathematical model for a two bed adsorption cooling cycle has been developed with the cycle modified to produce power by incorporating an expander between the desorber and the condenser. Results show that it is possible to produce power and cooling at the same time without affecting the cooling output. Results also show that for all adsorbents used as the heat source temperature increases, the cooling effect and power generated increase. As for increasing the cold bed temperature, this will decrease the cooling effect and power output except for SAPO-34 which shows slightly increasing trend of cooling and power output. As the condenser cooling temperature increases, the cooling effect and power output will decrease while for the chilled water temperature, the cooling load and power generated increased as the temperature increased. The maximum values of average specific power generation (SP), specific cooling power (SCP) and cycle efficiency are 73 W/kg_{ads}, 681 W/kg_{ads} (using SAPO-34) and 67% (using Silica-gel) respectively. However, MIL101Cr can generate SP and SCP of 95 W/kg_{ads} and 1367 W/kg_{ads} respectively, but this case cannot consider to be practical operating conditions, because of using relatively low cooling source temperature, but this material still offers potential of generating power.

1. Introduction

Global electricity demand has increased significantly over the last few decades leading to increase fossil fuel consumption and CO_2 emissions. Global warming, climate change and energy security lead researchers towards developing more environmentally friendly energy systems and real change in the energy policy [1]. Dependence on the fossil fuel can be reduced by using low grade heat sources such as solar energy, geothermal energy and waste heat. A number of researchers have investigated the use of sorption technologies to exploit low grade heat sources for cooling applications. Cai et al. [2] studied experimentally a single effect absorption system and results show that NH_3–$LiNO_3$ presents COP of 0.15 and minimum evaporation temperature of −13.1 °C utilising regeneration temperature of 94.6 °C, while using NH3–NaSCN presents COP of 0.2 and minimum evaporation temperature of −7.5 °C utilising regeneration temperature of 97.6 °C. Gomri [3] simulated a solar/natural gas single effect lithium bromide absorption chiller and results show that COP of 0.82, exergy efficiency of 30% and 5 °C of evaporator temperature can be achieved utilising 54–83 °C of heat source temperature. Aiming to improve the adsorption cooling technology different system configurations, working pairs and heat and mass transfer enhancing technologies have been used [4]. Huizhong et al. [5] tested experimentally a solar powered adsorption cooling tube using active carbon/methanol and utilising heat source temperature of around 110 °C and results show that COP is about 0.11 and the evaporator temperature reached −4 °C. Jribi et al. [6] have set up a mathematical model of a 4-bed adsorption chiller using Maxsorb III -CO_2 utilising heat source temperature of 95 °C and results show that COP of 0.1 can be achieved. Low-grade heat sources, can be used to produce power (electricity) using Organic Rankine cycle (ORC) and Kalina cycle technologies. Lecompte et al. [7] examined ORC using zeotropic mixtures and

* Corresponding author.
E-mail addresses: fna397@bham.ac.uk, fadhelnor@gmail.com (F.N. Al-Mousawi).

http://dx.doi.org/10.1016/j.enconman.2016.08.012
0196-8904/

Nomenclature

Symbols

A	adsorption potential, J/mol
c_p	specific heat capacity, J/kg K
k_o	empirical constant in Eq. (8), 1/s
E_a	activation energy, J/kg
h	enthalpy, J/kg
h_{fg}	evaporation latent heat J/kg
M	mass, kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
Q_{st}	isosteric heat of adsorption, J/kg
R	gas constant, J/kg K
R_p	adsorbent practice radius, m
U	overall heat transfer coff., W/m^2 K
W	power generated W
SP	specific power generated W/kg$_{ads}$
SCP	specific cooling power W/kg$_{ads}$
t	time, s
T	temperature, K
x	adsorption uptake, kg/kg$_{ads}$
x_{eq}	equilibrium uptake, kg/kg$_{ads}$
φ	flag

Subscript

ads,a	adsorbent
ads	adsorption
bed	adsorbent bed
chill	chilled water
des	desorption
ex	expander
eff	effective
evap	evaporator
f	liquid
g	gas
i	adsorption/desorption
in	inlet
j	cooling/heating source
o	outlet
ref	refrigerant
r	ratio
s	saturation
cond	condenser
w	water

results show that the second law efficiency can be increased in the range of 7.1% and 14.2% compared to pure working fluids using heat source temperature of 150 °C. Elsayed et al. [8] numerically studied Kalina cycle system 11 (KCS11) and results show that efficiency can be improved by up to 40% using ammonia and up to 20% using R134a compared to ORC.

Both cooling and power have been recently investigated by a number of researchers to enhance the overall efficiency of utilising low grade heat sources. Table 1 summarises the research work carried out for producing cooling and power simultaneously. It can be seen that using absorption technology, cycle thermal efficiency of almost 27.7% can be achieved using low grade heat sources of temperature ranging from 57 to 465 °C and ammonia-water as working pair, however ammonia is toxic material and can cause serious health risk. Also, it can be seen that adsorption technologies have been used to produce cooling and power with COP of 0.77 and exergy efficiency of 90%.

The integration of adsorption system with Organic Rankine cycle to produce cooling and power was investigated by Jiang et al. [23] and Wang et al. [24] showing the possibility of generating cooling and power at the same time. However, the adsorption materials used by Jiang et al. is a chemical salt and that used by Wang et al. is the conventional silica-gel with limited water adsorption capability. There is a limited work to produce cooling and power by incorporating an expander in the adsorption system using chemical adsorbent materials such as $MnCl_2$ and $CaCl_2$ with ammonia as refrigerant [14–19], while no similar work was reported using physical adsorption materials. Chemical adsorbents have lower stability than a physical adsorbents, where chemical molecules do not keep their original state which limits its practical applications. Swelling and agglomeration are additional problems of chemical adsorbents which affect the mass and heat transfer performance of the system negatively [25].

Recently, advanced adsorption materials were developed like AQSOA-Z02 and various Metal Organic Framework materials like MIL101Cr with superior adsorption characteristics. Therefore this work investigates the performance of these advanced materials using two bed adsorption system to simultaneously produce cooling and power. In addition, the water adsorption characteristics of AQSOA-Z02 (SAPO-34) and MIL101Cr were measured using DVS analyser (dynamic vapour sorption analyser).

2. Basic adsorption cooling system

Fig. 1a shows a schematic diagram of a basic two-bed adsorption cooling system which consists of adsorber, desorber, condenser and evaporator As the adsorption is an exothermic process a cooling source is used to extract heat from the adsorber and sustain cooling during adsorption process which helps to desorb the refrigerant from the evaporator and produce cooling effect. Desorption is an endothermic process, and a heat source (low grade heat source) is used to add heat to the desorber and sustain heating during the process which helps to release the refrigerant (water vapour) from the hot bed. After that, the hot refrigerant will be cooled in condenser to feed the evaporator with the refrigerant liquid and keep the cooling process continuous. Fig. 1b shows the basic adsorption cycle on an isosteric diagram; process 1-2 is an adsorbent isosteric heating where a low grade heat source is used and this heating is still continuous during the process 2-3′ while the valve 4 is opened, after that, an adsorbent isosteric cooling is started (process 3′-4′) using cooling source and this cooling is still continuous during the process 4′-1 while the valve 1 is opened and the same processes are repeated for the other bed.

3. Adsorption system for cooling and power generation

Fig. 2a shows a schematic diagram of the modified two-bed adsorption cycle for cooling and power generation which consists of adsorber, desorber, condenser, evaporator and expander (turbine) which located between the hot bed (desorber) and the condenser. Adding an expander to the adsorption cycle is not enough to generate power without a significant pressure difference between the inlet and the outlet of the turbine which comes from