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Thermodynamic performances of a solar driven adsorption system

Md. Parvez Islam *, Tetsuo Morimoto

Department of Biomechanical Systems, Faculty of Agriculture, Ehime University, 3-5-7 Tarumi, Matsuyama 790-8566, Japan

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ABSTRACT

This study examines the thermophysical process of a solar driven adsorption cooling system. The data used for the performance study were taken experimentally during the start-up procedure of a solar collector. The generation of high temperatures inside a solar collector adsorption tube is a challenge due to the intermittent nature of solar radiation. In this present study, a solar collector adsorption tube using granular activated carbon (GAC1, GAC2) and methanol is introduced. The proposed system maintains higher adsorption temperatures up to 117.2 °C. The evaporator temperature of the solar adsorption cooling system decreased to −12 °C (sunny day) and 0 °C (sunny-cloudy days), allowing liquid water converted to solid ice. This result showed that a solar collector filled with granular activated carbon and methanol successfully produces ice inside the solar adsorption cooling system throughout the experiment period. A solar-powered pump circulated the melted ice inside the storage chamber during day time and thus decreased the inside temperature of storage chamber to 15 °C and 10 °C for shorter and longer durations, respectively.

1. Introduction

Solar thermal based cooling system is one of the renewable source of cooling with various advantages, such as short installation time and long–life operation, simplicity, without moving parts, silent, safe and non–polluting (Balzani and Reatti, 2005). Solar–driven adsorption cooling systems in recent years have been receiving more attention as a replacement for conventional vapor compression refrigeration cycles driven by electricity. Alghoul et al. (2007) stated that a solid adsorbent (GAC) and liquid adsorbate (ethanol) is the appropriate working pairs for producing ice in a low energy (flat–plate solar collector) based solar adsorption cooling system. The highest COP of a GAC–ethanol based cooling system is found when the regeneration temperature is above 70 °C (Habiba et al., 2014).

This technology is particularly attractive when a high amount of low-temperature heat is available, such as solar thermal energy (Wang and Oliveira, 2006) and weather fluctuations that lead to changes in the cooling load, and the cooling capacity of the system (Alkhair et al., 2015; El-Sharkawya et al., 2014; Habiba et al., 2013).

The major component of a solar adsorption cooling system is the flat-plate solar collector. Alam et al. (2013) stated that the optimization of the cycle time reduces collector size. The collector first absorbs incoming solar radiation and then converts it to thermal energy that heats up refrigerant fluid flowing through the collector. The whole process is affected by incoming solar radiation, duration of sunlight, and the thermal properties of the collector adsorption tubes, glazing materials, heat insulators, and transparent cover.

Yadav and Bajpai (2012) experimentally investigated the performance of a flat-plate solar collector with evacuated adsorption tubes and found that the solar collector with adsorption tubes has better thermal performance than a flat-plate solar collector without adsorption tubes. The main objective of this study is to develop a solar-driven adsorption cooling system with storage chamber and to investigate its thermal performance under different climatic conditions.

2. Materials and methods

2.1. Flat-plate adsorption solar collector

The construction of a flat-plate solar collector with polystyrene foam casing, blackened absorber surface, and transparent cover sheets is shown in Fig. 1a and b. The adjustable stand mounted solar collector is inclined toward the horizon of 80 °C (summer) and oriented to the south (Boxwell, 2015). The dimension of the rectangular casing is 1700 × 1000 × 300 × 50 mm and well insulated by 30 mm thick Rockwool. The insulated material provides sealing and reduces heat loss from the back or sides of the collector casing. The thermophysical properties of the insulating materials,

* Corresponding author.
E-mail address: engr_parvezfpm@agr.ehime-u.ac.jp (M.P. Islam).

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Nomenclature

A	area, m^2
T_{amb}	ambient temperature, °C
N	number of transparent covers
ε_{pl}	absorber plate emissivity
ε_{gc}	transparent cover emissivity
U	overall heat transfer coefficient, W/m^2 K
u	specific internal energy, J/kg
χ^*	adsorbed phase concentration ratio at equilibrium, kg/kg
Wo	maximum adsorption capacity, m^3/kg
q_{sh}	isosteric heat of adsorption or desorption, J/kg
C	specific heat, J/kg·K
D	constant in Dubinin-Astakhov equation
h	specific enthalpy, J/kg
L	latent heat of vaporization, J/kg
m	mass, kg
n	constant in Dubinin-Astakhov equation
P	pressure, Pa
T	temperature, K
V	volume, m^3
Q	thermal energy, J
y	wetness fraction
I_T	incident solar radiation, W/m^2
t	time (s)
T_w	initial water temperature, °C
C_w	specific heat of water, kJ/kg·K
C_{ice}	specific heat of ice, kJ/kg·K
L_f	latent heat of ice fusion, kJ/kg
δm_{con}	differential mass of methanol vapor that flows towards the condenser tube

Greek symbols

∅	diameter, mm
σ	Stefan-Boltzmann constant
λ	wavelength
ω	hour angle, °
φ	latitude, °
ρ	density, kg/m^3
ε	porosity

Subscripts

sol	solar radiation
be	direct beam
gr	ground
sr	sky reflection
i	ambient air
p	porosity
at	adsorption tube
p	particle
e	evaporator
c	collector
D	difference/change
s	solid
gen	generation
con	condenser or condensation
vp	vapor pressure
max	maximum
min	minimum
ev	evaporator
amb	ambient or atmospheric
ads	adsorption
des	desorption
f	fluid or liquid
sh	heat of adsorption/desorption
ap	adsorbed phase
p	particle
tr	true

Abbreviations

COP	coefficient of performance
GAC	granular activated carbon

transparent cover and heat absorbing materials are shown in Table 1.

The collector casing is covered with a high transmittance Plexiglas *plate* (1940 × 940 × 3 mm). The optical and thermal properties of the Plexiglas made casing retaining the stagnant air layer between the absorber plate and the cover glass. It also reduces the convective losses from the absorber plate and adsorption tube. A 0.5 mm thick aluminium made blackened absorber plate with attached copper made adsorption tubes (∅40 mm) maximize the radiant energy absorption and transfer the absorbed heat to a working fluid (methanol) at a minimum temperature difference, and minimum radiant emission.

Fig. 1c shows an evacuated copper tube (∅15 mm) is placed inside a vacuum-sealed adsorption tube and attached to a blackened absorber plate. The space between the bigger and smaller diameter adsorption tube is filled with GAC and methanol. The length of the bigger and smaller diameter adsorption tubes are 1010 mm and 1000 mm, respectively. The adsorption tube is perforated with holes (∅0.3 mm), is hollow, and the inside space is evacuated. The perforated adsorption tube promotes the state change process of the liquid methanol inside the adsorption tube and eases methanol flow to and from the GAC. The methanol liquid within the adsorption tube heats and turns to vapor when solar radiation falls on the surface of the absorber plate and adsorption tube, and later evacuated through the link tubes. The closed ends of the adsorption tubes placed inside the casing through twelve holes (Fig. 1d).

2.2. Condenser

The condenser is an air–cooled heat exchanger which releases heat to the surrounding environment through fins. The methanol vapor (flows from the solar collector adsorption tube during desorption) is liquefied by the influence of natural air flow throughout the condenser and then stored in the storage tank, as shown in Fig. 3a. Later the condensed liquid methanol is gravity–fed to the evaporator using V_3 valve. As shown in Fig. 2a, the heat exchanging surface of the condenser is 900 × 460 mm consisting 80 copper fins (7 × 7 mm).

2.3. Evaporator

The evaporator stores the entire condensed methanol received from the condenser storage tank. The heat exchange surface of the evaporator is constructed as a series of six trapezoidal cells as shown in Fig. 2b (the dimensions of the evaporator are 320 × 210 × 100 mm). The evaporator is made of copper sheet and partly immersed in a water tank (Fig. 5), and both the evaporator and water tank are placed in a Rockwool box.

2.4. Storage chamber

The dimensions of the storage chamber are 520 × 520 × 320 × 50 mm. The storage chamber maintains lower temperatures during the daytime by circulating melted ice by a