Energy Conversion and Management 126 (2016) 548–560

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A thermal energy storage system provided with an adsorption module – Dynamic modeling and viability study

M.S. Fernandes [a,*], G.J.V.N. Brites [a], J.J. Costa [a], A.R. Gaspar [a], V.A.F. Costa [b]

[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, P-3030 788 Coimbra, Portugal
[b] TEMA (Center for Mechanical Technology and Automation), Department of Mechanical Engineering, University of Aveiro, P-3810 193 Aveiro, Portugal

ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 9 August 2016
Accepted 15 August 2016

Keywords:
Solar energy
Thermal energy storage
Domestic hot water
Adsorption
Modeling
Silica-gel/water pair

ABSTRACT

The dynamic model of a heat storage adsorption device is presented. The adsorption module operates with the silica-gel/water pair and is capable of storing the thermal energy received from the hot water of the storage tank where it is immersed, to give it back later as adsorption heat. The module is applied to a solar thermal energy system and assessed through a set of parametric tests. It is found that higher condenser lengths and larger pre-heating water tank volumes always improve the system's performance. For a selected fixed heat exchange area, smaller evaporator tube diameters are found to improve the system's performance, while reducing the number of tubes of a settled diameter has a negative effect. It is also found that the system's performance tends to decrease by increasing the main tank's volume, thus requiring even larger adsorbers for larger tanks. Throughout this exploratory study, the adsorption system always presents higher performances when compared with a similar conventional storage system (up to 16% savings in annual backup energy), showing promising perspectives for the overall optimization and application studies, and presenting an attractive solution to increase the thermal storage capacity of solar thermal systems.

1. Introduction

Sensible heat storage systems have relatively low energy storage density and require large storage volumes or higher temperatures, the latter of which leads to increased energy loss. The latent heat storage technology allows for a much higher energy storage density within a narrow temperature range. However, phase change materials present some limiting issues such as crystallization, ageing, and corrosion, and they can only store energy efficiently around the phase transition temperature level [1]. Although these are mature technologies and the most common processes employed in projects and plants worldwide, there are other technologies that allow for higher thermal energy storage densities, such as thermal energy storage based on sorption processes (absorption or adsorption).

In an adsorption storage device, a heat source promotes the dissociation of a working pair (desorption), whose substances can be stored separately for a long period of time (storage period). When they come into contact again (adsorption), an equal amount of heat is released, which can be used for useful heating purposes. Thus, in this kind of systems the adsorption heat is released by bringing together the two substances at the time when the useful heat is required. The physical separation of the substances enables a loss-free thermal energy storage, as the heat is not stored in a sensible or latent form, but as a potential [2,3].

Sorption heat storage is a technology that is the focus of research and development towards new applications, as it is a promising alternative to the conventional heat storage systems [4,5]. In comparison with conventional heat storage systems, adsorption storage systems are able to handle the temporary storage of thermal energy in an easier, more compact and efficient way, even for long storage periods, with negligible heat losses and high energy densities (higher than sensible or latent heat storage) [6,7]. Solar thermal energy, geothermal energy, biomass energy, thermal surplus energy or waste heat from several processes can be used as a heat source for thermal energy storage. This is thus a promising technology to integrate or even replace the heating production from fossil fuels or electric systems, reducing the CO_2 emissions and lowering the peaks of energy demand and the energy production levels. It can be a viable solution not only from the technical point of view, but also for economic reasons [8,9]. Practical feasibility of the adsorption thermal energy storage has already been demonstrated [2,10]. Furthermore, adsorption

* Corresponding author at: Departamento de Engenharia Mecânica, Faculdade de Ciências e Tecnologia da Universidade de Coimbra – Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal.
E-mail address: marco.fernandes@adai.pt (M.S. Fernandes).

http://dx.doi.org/10.1016/j.enconman.2016.08.032
0196-8904/

Nomenclature

A	area (m^2)
c	specific heat (J/(kg K))
c_p	constant pressure specific heat (J/(kg K))
D	diameter (m)
dt	time step (s)
e	thickness (m)
E_f	overall thermal effectiveness of the fins system (–)
g	gravitational acceleration (m/s^2)
h	convection heat transfer coefficient ($W/(m^2 K)$); height (m)
k	thermal conductivity (W/(m K))
l	length (m)
L	latent heat (J/kg)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
N_c	number of tube passes, in the condenser (–)
N_f	number of fins (–)
N_t	number of tubes (–)
Nu	Nusselt number (–)
p	pitch (m)
P	pressure (Pa)
Pr	Prandtl number (–)
Q	heat (J)
$\dot{Q}_{hx}$	thermal energy rate from solar heat exchanger (W)
Ra	Rayleigh number (–)
T	temperature (°C, K)
U	overall heat transfer coefficient ($W/(m^2 K)$)
V	volume (m^3)
x	distance (m)
X	adsorbed water content (dry basis) ($kg_{adsorbate}/kg_{dry-adsorbent}$)

Greek symbols

β	volumetric thermal expansion coefficient (K^{-1})
Δ	difference; variance (–)
ΔH_{ads}	heat of adsorption (J/kg)
ε	total porosity of the adsorbent bed (–)
η	efficiency (–)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

0	previous instant
a	adsorbent
ads	adsorber; system with adsorption module
bh	backup heater
c	condensation; condenser; contact
$conv$	conventional system
cs	cross-section
$down$	node below
e	evaporation; evaporator
env	environment
f	fin
h	hollow
i	inner
in	input
m	metal
$mains$	mains water
max	maximum value
o	outer
out	output
s	surface
sp	setpoint
t	tube
$tank1$	main tank
$tank2$	pre-heating tank
unf	unfinned
up	node above
v	vapor
w	water

cycles have already been applied in several research projects as a promising approach to promote thermal energy storage with relatively small storage volumes [5,8,11–13].

Currently, thermal energy storage of solar systems for domestic hot water (DHW) consists of one or more water tanks of considerable dimensions, as they store only sensible heat. Besides, a common characteristic of these systems is the need of backup heating, usually fueled by fossil or electric energy, when the available solar energy is not enough. The system proposed in this paper combines the characteristics of the adsorption heat storage with a conventional sensible hot water storage system. The simplicity of a hot water storage system is kept, while its performance is enhanced by the adsorption module. A silica-gel adsorber, placed inside the hot water tank, promotes the heat exchange with the water, while a condenser and an evaporator operate as heat sink and heat source, respectively, for the working fluid (water) phase changes. This storage system can be used with any heat source, but it is particularly suitable for working with solar energy, whose supply is neither possible to control nor coincident with the hot water demands. A comparison of the different thermal energy storage technologies applicable to DHW (including the here proposed system) can be found in Table 1.

This paper follows the work introduced in [14], in which an adsorber unit model for thermal energy storage is presented in detail, addressing now the complete model of the adsorption system. In the present work, the heat storage system with adsorption module is modeled using TRNSYS® and MATLAB®. The overall system is described, including its operation, and the corresponding model equations presented, as well as the solving methodology used. A set of results from parametric tests is then presented, aiming to evaluate the behavior of the system under different geometry configurations, mainly focusing on the new elements introduced here: condenser, pre-heating water tank (hereafter referred to as secondary tank), and evaporator. A study of the influence of the water tank volume on the system's performance is also presented, ending with a complete system assessment focusing in all components.

2. Description and operation of the proposed adsorption storage system

The main goal of the proposed system is to store up the excess (or unused) thermal energy (produced by solar collectors of a typical solar thermal storage system) by way of regenerating the adsorbent material in the adsorber immersed in the DHW tank, thus allowing for its use later on – through adsorption of the previously desorbed fluid – when the water inside the tank cools down below a certain temperature level. The adsorption system also aims to reduce the operation of the backup heating system. Furthermore, during the desorption phase, the condensation heat of the desorbed vapor could be recovered to preheat the cold water entering the tank. The present study follows a previous work [14],