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Modeling and parametric analysis of an adsorber unit for thermal energy storage

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ABSTRACT

The dynamic model of an adsorber unit used as thermal energy storage device immersed in water is presented. The system operates with the silica-gel/water pair and is capable of storing the thermal energy received from the surrounding water (*e.g.*, excess heat input from a hot water storage tank), in order to give it back later to the water as adsorption heat. The model was developed following a lumped parameter approach implemented in MATLAB® code. The performance of the absorber unit was assessed by a set of parametric tests under different geometric configurations and temperature conditions. The mass of adsorbent was found to have a higher impact on the thermal energy exchange than the surface contact area between metal and adsorbent. An improved finned adsorber, with 27 internal longitudinal fins and 120 external annular fins, resulted in a heat output to the water 2.3 times higher than with a similar finless adsorber. Moreover, the evaporation temperature effect was found to be much higher than the condensation temperature effect. This device seems to be an attractive solution to include, for instance, in solar hot water systems in order to fulfill the thermal energy needs during periods of low solar radiation.

1. Introduction

Sorption heat storage is a relatively new technology with much ongoing research and development, being a promising alternative to the conventional heat storage systems [1,2]. 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, an equal amount of heat is released (adsorption), 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 [3,4]. The basic adsorption cycle is sketched in Fig. 1 and its operation described in detail in Ref. [5].

Compared with latent or sensible heat storage systems, adsorption storage systems are able to handle the temporary storage of thermal energy in an easier, compact and efficient way, even for long storage periods, with negligible heat losses and higher storage densities [2,6,7]. Furthermore, adsorption cycles have already been applied in several research projects as a promising approach to promote thermal energy storage with relatively small storage volumes [5,8–10]. Solar thermal energy, geothermal energy, biomass energy, thermal surplus energy or waste heat from several processes can be used as heat source for the thermal energy storage.

This paper presents an adsorber unit which is capable of storing thermal energy received from the surrounding hot water (especially when there is excess heat available), and give it back later as adsorption heat, when the water temperature is lower. Possible examples of application of this unit are DHW (domestic hot water) systems or heating and cooling hybrid adsorption systems. At this stage, the study is focused on the development in MATLAB® of a suitable model for the adsorber. Therefore, the model equations are

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Nomenclature

A	area [m^2]
c	specific heat [J/(kg K)]
c_p	constant pressure specific heat [J/(kg K)]
D	diameter [m]
D_{s0}	surface diffusion coefficient [m^2/s]
dt	time step [s]
E_a	activation energy of surface diffusion [J/mol]
e_a	adsorbent thickness [m]
E_f	global thermal effectiveness of the fins system [−]
e_f	fin thickness [m]
g	gravitational acceleration [m/s^2]
h_c	contact heat transfer coefficient between metal and adsorbent [W/(m^2 K)]
h_f	fin height [m]
h_o	convection heat transfer coefficient between water and metal [W/(m^2 K)]
K_0	pre-exponential constant [kg/(kg Pa)]
L	bed length [m]
m	mass [kg]
N_f	number of fins [−]
Nu	Nusselt number [−]
P	pressure [Pa]
Pr	Prandtl number [−]
Q	heat [J]
q_m	monolayer capacity [kg$_{\text{adsorbate}}$/kg$_{\text{dry adsorbent}}$]
R	universal gas constant [J/(mol K)]
R'	particular gas constant [J/(kg K)]
Ra	Rayleigh number
R_p	average radius of adsorbent granule [m]
t	time [s]
T	temperature [°C, K]
V	volume [m^3]
X	content of adsorbate in dry adsorbent [kg$_{\text{adsorbate}}$/kg$_{\text{dry adsorbent}}$]

Greek symbols

β	volumetric expansion coefficient [K^{-1}]
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]
τ	Tóth equation constant [−]

Subscripts

0	previous instant
a	adsorbent
bed	adsorbent bed
c	condensation
e	evaporation
eff	effective
eq	equilibrium
f	fin
h	hollow
i	inside
m	metal
o	outside
p	primary
part	particle
r	adsorbed phase
unf	unfinned
v	vapor
w	water

presented, as well as the solving methodology and the model validation. A set of parametric tests is then presented aiming to evaluate the behavior of the adsorber unit under different geometry configurations and temperature conditions: varying mass and size, inclusion of internal and external fins, and varying condensation and evaporation temperatures.

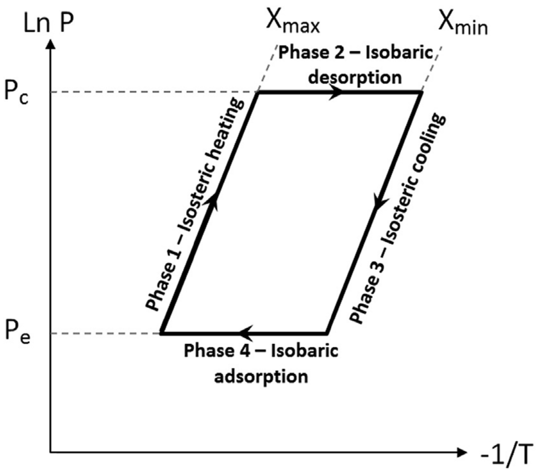

Fig. 1. Theoretical adsorption cycle (Clapeyron diagram).

2. Selection of the adsorption pair

There are several possible working pairs that can be used in adsorption thermal storage systems. Refs. [2,6,9,11,12] reviewed or/and analyzed several adsorbent materials and working pairs, presenting the technical challenges and perspectives for adsorption thermal storage technology. In the present case, the heat source is the hot water surrounding the adsorber, which, assuming a conventional DHW system, is typically heated by low temperature heat sources (*e.g.*, thermal solar collectors). Also, a great amount of adsorption heat is desirable, but that leads to high desorption temperatures in the charging mode, which may not be achievable with typical thermal solar collectors.

From the studied working pairs, silica-gel and water pair is the one that better fulfill the above criteria. In fact, this working pair could reach a theoretical energy density of 220 kWh/m^3, almost 4 times that of a water storage tank with a temperature change between 40 °C and 90 °C with no heat losses (57 kWh/m^3) [12]. Silica-gel/water presents an adsorption heat lower than other working pairs, but it requires only low grade heat sources, commonly below 85 °C. Moreover, water is completely safe regarding the risk of contamination of the potable water surrounding the adsorber unit [13–15]. In addition, the silica-gel/water working pair is well-known, tested in several adsorption thermal storage projects and in adsorption refrigeration projects [9,16,17]. Therefore, the silica-gel and water adsorption pair was selected to develop the present study.