Applied Thermal Engineering 87 (2015) 412–423

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Application of the novel ETS-10/water pair in cyclic adsorption heating processes: Measurement of equilibrium and kinetics properties and simulation studies

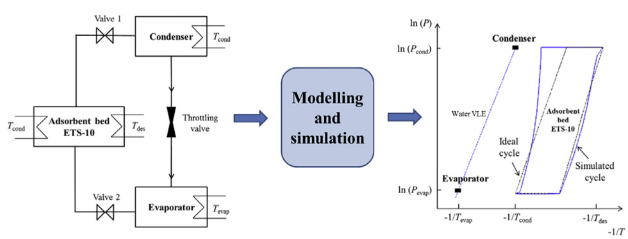
Joana M. Pinheiro [a], Anabela A. Valente [a], Sérgio Salústio [b], Nelson Ferreira [b], João Rocha [a], Carlos M. Silva [a, *]

[a] *CICECO - Aveiro Institute of Materials, Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal*
[b] *Department of R&D of Bosch Thermotechnology, Cacia-Aveiro, 3800-533, Portugal*

HIGHLIGHTS

- Modelling & simulation of a cyclic adsorption heating unit using novel ETS-10/water pair.
- Equilibrium isotherms and thermo-physical data of ETS-10 measured here for the first time.
- COP = 1.36 and SHP = 934 W kg_S^{-1} were obtained for bed thickness of 2 mm.
- The overall heating performance was highly influenced by geometric/operating conditions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 November 2014
Accepted 8 May 2015
Available online 19 May 2015

Keywords:
ETS-10/water
Isotherms
Thermophysical properties
Cyclic adsorption heating process
Modelling
Simulation

ABSTRACT

The ETS-10/water pair was explored for the first time for cyclic adsorption heating purposes, with modelling and simulation studies. Measurements of water adsorption equilibrium properties were carried out, and, for the first time, the effective thermal conductivity and specific heat capacity of ETS-10 were measured. The experimental results were used for the modelling and simulation of an adsorption heating unit. A model was developed, which contemplates adsorption equilibrium, one-dimensional heat and mass transfer in the bed, heat transfer in the external film, and intraparticle mass transport. From the numerical simulations, the coefficient of performance (COP) and specific heating power (SHP) were calculated, which allowed evaluating the heating performance of the adsorption unit. The bed thickness, adsorbent regeneration temperature, and heating thermal fluid temperature influence considerably the cycle time and cyclic adsorption loading swing, thus impacting on COP and SHP. For three simulated cycles differing in bed thickness, COP values in the range 1.36–1.39 were obtained, which are close to the estimated ideal value of 1.41; the corresponding SHP ranged from 934 to 249 W kg_S^{-1}. Based on sensitivity studies, a good compromise is required between the bed thickness, regeneration temperature, and the heating fluid temperature in order to meet superior performances of the system.

* Corresponding author. Tel.: +351 234 401 549; fax: +351 234 370 084.
E-mail address: carlos.manuel@ua.pt (C.M. Silva).

http://dx.doi.org/10.1016/j.applthermaleng.2015.05.011
1359-4311/

1. Introduction

In recent years adsorption systems for heating/cooling applications have received much attention, since they are based on an environmentally friendly technology in comparison to the conventional vapour compression systems, and can be powered by thermal energy sources such as solar energy or waste heat [1–4]. The absence of moving parts, noise and vibration are also important features of adsorption systems [5].

A basic adsorption heating system (AHS) comprises an adsorbent bed operating in alternate connection to an evaporator or a condenser (Fig. 1a), depending on the stage of the cycle. The complete adsorption cycle consists of four stages (Fig. 1b): isobaric adsorption (1–2), isosteric heating (2–3), isobaric desorption (3–4), and isosteric cooling (4–1). In the isobaric adsorption stage, the bed is connected to the evaporator, vapour is adsorbed on the adsorbent material and heat Q_{1-2} is released from the system, which can be used for heating purposes. Subsequently, in the isosteric heating (2–3) the adsorbent is isolated (closing valves 1 and 2) and heated (Q_{2-3}), which is accompanied by increasing pressure. When P_5 is reached, the adsorbent bed is opened to the condenser, and the isobaric desorption stage is initialized. Heat supply (Q_{3-4}) is required for regenerating the adsorbent; the desorbed vapour condenses inside the condenser, releasing heat (Q_5) which can be used for heating purposes. The adsorption cycle closes with the isosteric cooling stage in which the bed is isolated (closing valves 1 and 2) and cooled, which is accompanied by pressure drop. The sensible heat released by the system in this stage (Q_{4-1}) can also be used for heating purposes. When the bed pressure reaches P_6, a new cycle can be initialised by reopening the adsorbent bed to the evaporator, etc.

The selection of the most appropriate working adsorbent/adsorbate pair is one of the main factors determining the efficiency of any AHS. Important requirements to be put on the adsorbent include good hydrothermal stability, considerable adsorption capacity, and easily regenerated. On the other hand, the refrigerant fluid should preferably have a large specific latent heat, good thermal stability, be non-toxic and not flammable [4]. Some of the pairs reported in the literature for heating applications include activated carbon/methanol [6], activated carbon/ammonia [7] and zeolite/water [6]. Nevertheless, there is a continuous search for novel materials aiming at the improvement of their heating performances [8,9].

The Engelhard titanosilicate number 10 (ETS-10), firstly synthesised in 1989 [10], possesses an interesting framework structure and charge distribution, and unique adsorption properties [11]. This material is microporous and crystalline, and its structure consists of corner-sharing SiO_4 tetrahedra and TiO_6^{2-} octahedra linked through bridging oxygen atoms, forming a pore system which contains 12-membered ring channels. Since the titanium sites are located in small 7-membered ring channels, the interactions between water molecules inside the 12–membered ring channels and the framework are relatively weak in comparison to conventional zeolites, allowing facilitated regeneration of ETS-10 [12]. The potentiality of ETS-10 as adsorbent in cyclic processes for removing water has deserved patent applications [13], and it has also found increasing interest as desiccant in chlorofluorocarbon-free air conditioners based on evaporative and desiccant cooling [14]. In spite of its interesting water adsorption properties, ETS-10 has been under-investigated for cyclic adsorption heating purposes. This may be partly due to the fact that the design and optimisation of heating/cooling systems require the knowledge of various fundamental properties of the adsorbents, which unfortunately are not available for many promising materials including ETS-10.

In this work, a cyclic adsorption unit with the ETS-10/water pair was investigated for heating purposes. The process was simulated using a model, which includes the adsorption equilibrium, one-dimensional heat and mass transfer phenomena in the bed, heat transfer in the particle film, and mass transfer resistance inside the particles. Due to the lack of necessary kinetics and equilibrium data for the simulations, this work comprehended also an indispensable experimental component. The ETS-10/water isotherms were measured at different temperatures, and the data fitted with a reliable model for determination of the isosteric heat of adsorption; from the adsorption kinetics

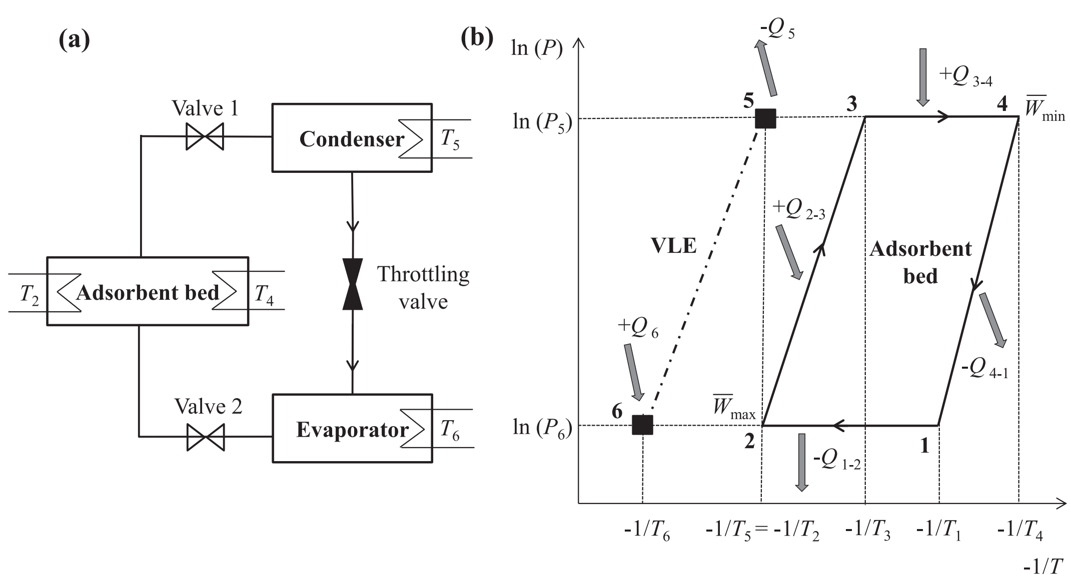


Fig. 1. (a) Simplified representation of an adsorption heating system and (b) corresponding Clapeyron diagram. Q_{1-2}, Q_{4-1} and Q_5 are the heats generated during adsorption stage, during isosteric cooling stage and in the condenser, respectively; Q_{2-3}, Q_{3-4} and Q_6 are the heats consumed during isosteric heating stage, during desorption stage and in the evaporator, respectively; P_5 and P_6 are the condenser and the evaporator pressures, respectively; T_5 and T_6 are the condenser and the evaporator temperatures, respectively; T_1 and T_2 are the initial and final temperatures of the bed during isobaric adsorption stage; T_3 and T_4 are the initial and final temperatures of the bed during isobaric desorption stage; $\overline{W}_{max}$ and $\overline{W}_{min}$ are the maximum and minimum average adsorbate loadings, respectively.