# The effect of cycle boundary conditions and adsorbent grain size on the water sorption dynamics in adsorption chillers

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## ABSTRACT

The aim of this work was an experimental study of the temporal evolution of isobaric adsorption uptake (release) for simplest configuration of an adsorbent-heat exchanger unit, namely, a monolayer of loose adsorbent grains located on a metal plate. The study was performed by a large temperature jump method at four various boundary conditions of an adsorptive heat transformation cycle typical for air-conditioning application driven by low temperature heat: $T_e$ = 5 and 10 °C, $T_c$ = 30 and 35 °C and $T_{HS}$ = 80 °C. The size of the Fuji silica grains was varied from 0.2 to 1.8 mm to investigate its effect on water sorption dynamics. For each boundary set and grain size the experimental kinetic curve could be described by an exponential function up to 80–90% of the equilibrium conversion. Desorption runs are found to be faster than appropriate adsorption runs by a factor of 2.2–3.5, hence, for optimal durations of the isobaric ad- and desorption phases of the chilling cycle should be selected accordingly. The size $R$ of the adsorbent grains was found to be a powerful tool to manage the dynamics of isobaric water ad-/desorption. For large grains the characteristic time was strongly dependent on the grain size and proportional to $R^2$. Much less important appeared to be an impact of the boundary conditions which variation just weakly affected the dimensionless kinetic curves for the four tested cycles. The maximal specific cooling/heating power was proportional to the maximal temperature difference $\Delta T$ and the contact area $S$ between the layer and the metal plate, and can exceed 10 kW/kg. The heat transfer coefficient $\alpha$ estimated from this power was as large as 100–250 W/($m^2$ K) that much exceeds the value commonly used to describe the cycle dynamics.

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## 1. Introduction

Adsorptive heat transformers (AHTs) are considered as a viable alternative to common compression systems [1,2]. The latter have been carried to nearly perfection if the driving energy is electricity that is now in increasing demand. In contrast, AHTs do not consume electricity and can be driven by barely heat that is much more available. Moreover, this can be a low temperature heat at $T$ = 50–90 °C that is now unproductively wasted. To be competitive, AHT should be optimized from both thermodynamic and dynamic aspects. This paper is addressed to dynamic optimization of AHTs, and our approach is based on the idea that it is obligatory to consider the adsorbent and heat exchanger (A-HE) as an integrated unit and to measure dynamic properties of this unit under real operating conditions of AHT [3].

A basic three temperature (3T) AHT cycle consists of two isosters and two isobars (Fig. 1a) and is uniquely characterized by a set of the three boundary temperatures ($T_e, T_c, T_{HS}$) where $T_e$ is the evaporator temperature, $T_c$ is the condenser temperature and $T_{HS}$ is the temperature of the external heat source. The uptake (release) temporal evolution $q(t)$ *uniquely* characterizes the main dynamic features of isobaric stages "4 → 1" and "2 → 3" of AHT. These stages make the capital contribution to the coefficient of performance (COP) and the specific cooling power (SCP), while the isosteric stages "1 → 2" and "3 → 4" are short and less significant as a rule.

The aim of this study was to measure the function $q(t)$ for the simplest configuration of A-HE unit, namely, a monolayer of loose adsorbent grains (Fig. 1b), at various boundary conditions ($T_e, T_c, T_{HS}$) of heat transformation cycle. In this paper, we fixed the regeneration temperature $T_{HS}$ at 80 °C and considered the four boundary sets (5, 30, 80), (10, 30, 80), (5, 35, 80) and (10, 35, 80) which correspond to typical air-conditioning applications driven by low temperature heat. The size of the adsorbent grains was varied from 0.2 to 1.8 mm to investigate its effect on water sorption dynamics. We have selected a silica gel type RD manufactured by the Fuji Silysia Chemical Ltd. as an adsorbent of water vapor because exactly this material was used in commercialized adsorption chillers which utilize low-temperature heat (50–80 °C) [4,5]. This silica was studied in details by many authors, e.g. experimental equilibrium data for water adsorption were reported in [6–8] and mathematical equations for approximation of these data were presented in [6–9].

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## Nomenclature

| | | | | |
|---|---|---|---|---|
| AHT | adsorptive heat transformer | | $t$ | time, s |
| A-HE | adsorbent-heat exchanger | | $T$ | temperature, °C |
| COP | coefficient of performance | | $W$ | specific power, kW/kg |
| $D$ | diameter of the circle covered by the layer, mm | | | |
| $d_{av}$ | average gap thickness between a grain and a metal plate, mm | | *Greek symbols* | |
| | | | $\alpha$ | heat transfer coefficient, W/(m$^2$ K) |
| $h_{fg}$ | latent heat of water vaporization (2478 kJ/kg) | | $\Delta$ | difference operator (–) |
| $K$ | slope, W/(kg K) | | $\tau$ | characteristic time (s) |
| LDF | linear driving force | | $\lambda$ | thermal conductivity, W/(m K) |
| LTJ | large temperature jump | | | |
| $P$ | water vapor pressure, mbar | | *Subscripts* | |
| $q$ | water uptake, g/g | | e | evaporator |
| $R$ | average grain radius, mm | | c | condenser, contact |
| $S$ | area of the circle covered by the layer, m$^2$ | | g | grain |
| SCP | specific cooling power, kW/kg | | HS | heat source |

To learn the effect of cycle boundary conditions and adsorbent grain size on the water sorption dynamics under real operating conditions of AHT, we used a new method of the large temperature jump (LTJ) [3,10]. This method allows experimental modeling the dynamics of isobaric stages of AHT, and studying the effects of adsorbent nature (Fuji silica RD, FAM-Z02, SWSs) [11], heating rate [10], non-adsorbable gas [11,12] and isobar shape [13] on the uptake evolution and AHT specific power.

## 2. Experimental procedure

The detailed diagram of the LTJ procedure and an experimental setup were presented elsewhere [10,12]. The LTJ method allows measuring the uptake curves for adsorbent layer located on a metal holder (fin) subjected to a fast temperature jump (from the minimal desorption temperature $T_2$ to $T_{HS}$) or drop (from the maximal adsorption temperature $T_4$ to $T_c$). The adsorption (desorption) process initiates a small variation of the vapor pressure $P(t)$, so that the water sorption process can be considered as quasi-isobaric, that is a close analogy of isobaric AHT stages. The temperatures $T_2$ and $T_4$ were taken directly from the working cycle diagram plotted for each boundary set from the equilibrium adsorption data [8].

Data of the pressure evolution $P(t)$ required for calculating the water uptake $q(t)$ were recorded each 1 s by a data acquisition system. The dimensionless *uptake* was calculated as

$$\frac{q_t}{\Delta q} = \frac{q(t) - q(t=0)}{q(t \to \infty) - q(t=0)} \tag{1}$$

The accumulated error in the absolute water loading showed a maximum *value* of ±10$^{-3}$ kg/kg that leads to the accuracy of the differential water loading $q(t)$ equal to ±3%.

The adsorbent grains of four various sizes were tested as fractions 0.2–0.25, 0.4–0.5, 0.8–0.9, and 1.6–1.8 mm. The weight of dry sample was 0.157 ± 0.002 g that corresponded to a monolayer of loose grains of 0.20–0.25 mm size covering a circle of 41.0 mm diameter on the metal plate. The dry sample weight was maintained constant, so that for large grains the diameter $D$ of the circle covered by the layer (Table 1) and the heat transfer surface $S = \pi D^2/4$ were reduced accordingly.

## 3. Results and discussion

We studied the effects of the cycle boundary conditions and adsorbent grain size on the water sorption dynamics under conditions close to isobaric stages of AHT. The data obtained were used to estimate the specific cooling (heating) power and the effective heat transfer coefficient between the plate and the adsorbent layer.

### 3.1. Sorption dynamics

Important finding is the fact that for each boundary set and grain size the experimental kinetic curve $q(t)$ can be described by an exponential function $q(t) = q(0) \pm \Delta q \exp(-t/\tau)$ up to 80–90% of the final conversion (Fig. 2). This is in good agreement with our previous results for the monolayer configuration [10,3,11,12] and shows the validity of this approximation for any boundary conditions. Surprisingly, the complex coupled heat and mass trans-
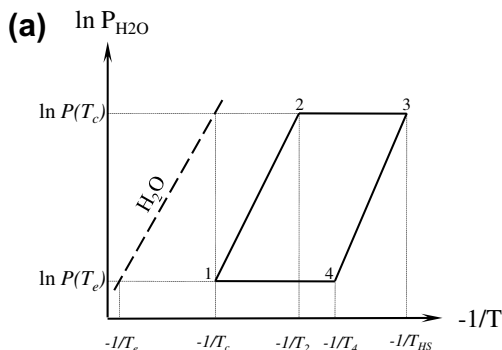
**(a)** ln P$_{H2O}$

**(b)**



**Fig. 1.** (a) The basic 3T cycle of AHP in the Clapeyron diagram. (b) The measuring cell with loose grains on the metal support exposed to temperature jump/drop.