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Dynamics of water vapour adsorption by a monolayer of loose AQSOA™-FAM-Z02 grains: Indication of inseparably coupled heat and mass transfer

Ilya S. Girnik [a, b], Yuri I. Aristov [a, b, *]

[a] Boreskov Institute of Catalysis, Pr. Lavrentieva 5, 630090, Novosibirsk, Russia
[b] Novosibirsk State University, Pirogova st, 2, 630090, Novosibirsk, Russia

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ABSTRACT

Dynamics of water adsorption in an adsorption chiller (AC) determines the specific cooling power and the AC size. The dynamics, in its turn, strongly depends on the configuration of an "adsorbent – heat exchanger" (Ad-HEx). Here we considered the simplest, monolayer, configuration of the Ad-HEx and studied the water ad-/desorption dynamics as a function of the grain size (0.2–2.1 mm), temperature drop (16–36 °C), and pressure (7–47 mbar) for a commercial adsorbent AQSOA™-FAM-Z02. The dynamics was measured by a Volumetric Large Temperature Jump method under typical conditions of isobaric stages of real AC cycle.

It is found that the initial part of all kinetic curves is exponential and can be described by a single characteristic time τ. This time depends on the grain size R as $\tau \sim R^{\alpha}$, where the index α is constant over the whole range of the grain sizes, and its value is 1.33 and 1.20 for adsorption and desorption runs, respectively. The α-constancy may indicate an inseparable coupling of heat and mass transfer in the monolayer configuration of AQSOA™-FAM-Z02 adsorbent bed. For grains of about 2 mm size, quite acceptable initial power (>2 kW/kg) is obtained. Thus, the monolayer configurations may result in fast adsorption dynamics, reasonable specific power and compact AC units.

1. Introduction

Despite a significant progress in adsorption chillers (ACs) achieved [1–4], still there is much room for further improving these systems, first of all, for enhancing the AC dynamics and reducing the AC size [1,5–7]. Since intrinsic adsorption is fast, the AC dynamics depends mainly on the rate of heat and mass transfer (HMT) in an "adsorbent bed – heat exchanger" (Ad-HEx) unit. Two basic configurations of the Ad-HEx units were considered in the literature [8–11]: a) a bed of loose adsorbent grains that contact with the HEx surface, and b) a consolidated adsorbent layer attached to the HEx surface. It has recently been reported [7,12,13] that the first configuration can ensure high values of the Specific Cooling Power (SCP) of 1–5 kW/(kg adsorbent) and more, in spite of prevailing modern trend that acceptable SCPs can be obtained only by using consolidated layers. Moreover, a direct comparison of the two mentioned concepts made in Ref. [11] clearly demonstrated that both the Coefficient Of Performance (COP) and SCP related to the HEx total volume were significantly larger for the loose grains configuration: COP = 0.4 and 0.24; SCP = 212 and 93 kW/m^3, respectively [11]. Besides, the loose grains configuration is much cheaper and more reliable with reference to the hydrothermal and mechanical stabilities under multiple cycling [11]. The adsorbent used for comparison was a commercial material AQSOA™-FAM-Z02, that is a silicoaluminophosphate (SAPO-34) specifically developed by Mitsubishi Plastics Ltd. for ACs [14].

Further important step on the dynamic optimization of real ACs utilizing the AQSOA™-FAM-Z02 was made in Ref. [15] that presents the systematic study on how a number of the adsorbent layers (N = 2, 4, and 8), grain size (0.2–0.9 mm) and cycle boundary temperatures affect the water adsorption dynamics. The loose grains configurations tested in that paper present a quite realistic situation, e.g. a compact Ad-HEx of the finned flat-tube type in which 2-8 adsorbent grains are housed inside a 1–2 mm gap between the fins [11,12,16]. This configuration corresponds to the ratio

* Corresponding author. Boreskov Institute of Catalysis, Pr. Lavrentieva 5, 630090, Novosibirsk, Russia.
E-mail address: aristov@catalysis.ru (Y.I. Aristov).

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Nomenclature

A	initial rate, g/s
d	layer thickness, mm
H	heat, J mol^{-1}
m	adsorbent mass, kg
N	number of the adsorbent layers, dimensionless
P	pressure, mbar
q	adsorption uptake, g/g
R	radius, mm
S	surface area, m^2
T	temperature, K, °C
t	time, s
U	heat transfer coefficient, Wm^{-2}K^{-1}
W	power, W; specific power, W kg^{-1}

Greek symbols

α	slope, dimensionless
Δ	increment
χ	dimensionless conversion degree
τ	characteristic time, s
ρ	layer density, kg/m^3
λ	thermal conductivity, W/(m·K)

Subscripts

av	average
ev	evaporation
0	initial
f	final
id	initial desorption
fd	final desorption
ia	initial adsorption
fa	final adsorption
ev	evaporation
max	maximal
0.5	50% conversion
0.8	80% conversion
0.9	90% conversion

(S/m) = <heat transfer surface>/<adsorbent mass> = (0.8–3.5) m^2/kg that, according to [12], can ensure high values of both COP and SCP.

In this paper, we consider a special case of flat monolayer configuration ($N = 1$). It is commonly deemed not to be optimal, because the mass of adsorbent grains housed in the monolayer is expected to be small as compared with the inert masses of AC unit. This is certainly true for small adsorbent grains, however, for grains that are large enough, their mass can be sufficient to ensure acceptable COP. Indeed, several ACs with finned-tube heat exchangers filled with zeolite pellets tightly inserted between the HEx fins were presented in the literature [17–19]. For instance, the AC unit studied in Ref. [18] (Fig. 1a) contained 13.2 kg zeolite 13X (or 17.6 dm^3 volume) located inside the stainless steel HEx of 32.8 kg weight (or 34 dm^3 volume). The ratio M/m = ⟨HEx mass⟩/<adsorbent mass> = 2.5 allowed obtaining quite reasonable COP-values of 0.67 and 1.09 for cooling and heat pumping, respectively [18]. The ratio M/m = 1.5–3.5 is typical for AC prototypes described in the literature, e.g. 1.8 and 3.5 reported in Ref. [12], and 1.6 - in Ref. [20]. The heat exchanger surface and the size of 13X zeolite grains in monolayer were not specified in Ref. [18]. The grain size between 1.6 and 2.4 mm was suggested in Ref. [19] for monolayer configuration capable to getting both high SCP and COP.

Dynamic data obtained for the monolayer configuration are important themselves, because they can be directly compared with results of a numerical modelling of the water ad-/desorption dynamics in a single adsorbent grain. For this simple case, it is possible to use an advanced model developed in Ref. [21], which is based on an exact Fickian diffusion equation instead of a common Linear Driving Force model that is approximative (see discussion in Refs. [6,22]).

For the monolayer configuration, the effects of the adsorbent grain size, temperature drop and vapour pressure on the water ad-/desorption dynamics were experimentally studied and appropriate recommendations were made.

2. Experimental procedure

The detailed V-LTJ procedure was described in Ref. [23] whereas an experimental test rig used in this study was presented in Ref. [24]. The experimental setup contained three main

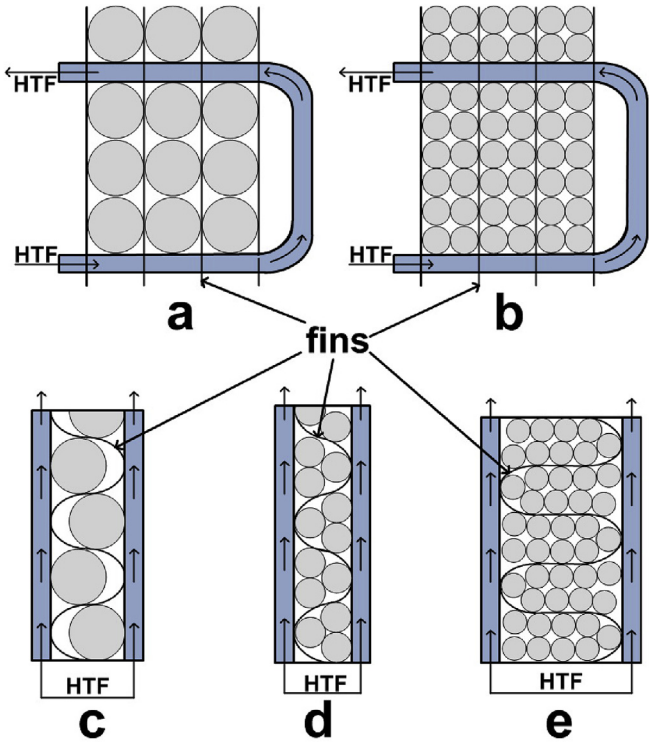

Fig. 1. Several monolayer configurations that can be realized in finned-tube heat exchangers with cylindrical (**a, b**) and plate (**c-d**) tubes. HTF stands for a heat transfer fluid.

compartments: the measuring cell (volume $V_{MC} = 0.14 \times 10^{-3}$ m^3), the vapour vessel ($V_{VV} = 30.5 \times 10^{-3}$ m^3) and the evaporator with liquid water (Fig. 2). Loose adsorbent grains were placed on an isothermal surface of the metal holder. Its temperature can be adjusted with the accuracy of ±0.1 °C using a heat carrier circuit coupled by a three-way valve (3 W V) either to circulating thermal bath 1 or 2.

The temperature of the constant volume vapour vessel as well as all connecting pipelines was maintained at 60 ± 0.5 °C by using the