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Water adsorption dynamics on representative pieces of real adsorbers for adsorptive chillers

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HIGHLIGHTS

- Small but representative pieces of finned flat-tube heat exchanger (HEx) are studied.
- A new gravimetric version of the large temperature jump method is used.
- The effects of the HEx geometry, grain size and water flow rate are evaluated.
- These tests confirm the existence of the "grain size insensitive" regime.

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ABSTRACT

Dynamic optimization of adsorbent-heat exchangers (Ad-HExs) represents a key issue for the broader diffusion of adsorption cooling and heating (ACH) technologies. This paper is a sequel to an earlier one (Sapienza et al., 2014) that described the study of an ideal Ad-HEx configuration (loose adsorbent grains placed on a flat metal plate) by a new gravimetric version of the large temperature jump method. In the present paper, the study is extended to analyse the dynamic behaviour of HExs with much more complex geometry, namely, small but representative pieces of a finned flat-tube HEx. The Ad-HEx configuration tested is obtained by filling these small HExs with loose grains of AQSOA FAM Z02. The aim of the study is to evaluate the effect of the HEx geometry, grain size and flow rate of heat transfer liquid. The results obtained are compared with a reference flat Ad-HEx configuration.

The ad-/desorption dynamics is found to be nearly exponential that proves the applicability of a modified Linear Driving Force model to characterize the water ad-/desorption rate. The majority of the tests have revealed the existence of the "grain size insensitive" regime for grains of 0.3–0.7 mm size. Under this mode, the dynamic behaviour is only function of the ratio $(S/m) = \langle$heat transfer surface$\rangle/\langle$absorbent mass$\rangle$. This leads to a practically important conclusion that it is not necessary to precisely select the adsorbent grain size. When the grain size becomes too small or too large the rate reduction was found that is due to inter- or intra-grain mass transfer resistances.

The tested Ad-HEx configuration is proved to be quite efficient: the specific cooling power amounts to 50–66% of that obtained with the reference (ideal) one, and the average specific cooling power $W_{80\%}$ can reach 2.3 kW kg^{-1}. This power is 6–8 times higher than those reported in the literature for full scale Ad-HExs with similar cell geometry. Thus, the study showed that there is still a big room for significant dynamical improvement of real ACH units.

1. Introduction

Rising in thermal comfort demand implies, through the use of traditional vapour compression air conditioning and refrigeration systems, an inevitable growth of energy consumption and related harmful emissions [1]. Adsorption cooling and heating (ACH) technology appears, in this context, as an alternative and attractive way to satisfy the mentioned demand. Indeed, it is able to join economical and ecological advantages especially in all cases in which a large amount of waste or free heat is available (namely solar, geothermal, district heat as well heat from tri-generation and automotive air

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Nomenclature

A	fin pitch, m
Ad-HEx	adsorbent-heat exchanger unit
ACH	adsorption cooling and heating
B	fin height, m
d	grain size; diameter, m
D	diffusivity, $m^2\ s^{-1}$
G-LTJ	gravimetric version of large temperature jump method
DH_{ads}	mean adsorption heat, $kJ\ kg^{-1}$
J	heat flux, W
L	HEx length, m
m	dry adsorbent mass, kg
M	total metallic mass, kg
P	pressure, Pa
R	radius, m
r	rate of ad-/desorption, $g\ g^{-1}\ s^{-1}$
S	surface area, m^2
T	temperature, K; HEx thickness, m
t	time, s
U	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
V	flow rate, $dm^3\ min^{-1}$
V-LTJ	volumetric version of large temperature jump method
w	water uptake, $g\ g^{-1}$
W	specific cooling power, $W\ kg^{-1}$; HEx width, m

Greek symbols

Δ	difference
λ	mean free length of vapour path, m
τ	characteristic time, s

Subscripts

0	initial stage
∞, inf	infinity
ads	adsorbent
des	desorption
Kn	Knudsen
l	liquid phase
m	molecular
max	Maximal
P	Poiseulle
v	vapour phase

conditioning systems). Some exhaustive reviews about the ACH units operation and their application fields can be found in [2–5]. Although using ACH technology involves a series of well-known profits (low electricity consumption, environmental friendly, noise and vibration free operation, etc.), it presents still crucial limitations to be overcome in order to allow its broader diffusion. Research activities have traditionally aimed at developing advanced adsorption cycles [6,7], realize new or improve the existent working pairs [8,9], design enhanced adsorbent bed [10] or systems [11–13]. Despite the efforts made, the ACH units performance is quite far from the perfection, especially in terms of the specific power [14,15], i.e. the power related to the adsorbent weight or volume.

For this reason, actual efforts are focused on developing diverse experimental methods to study adsorption dynamics in ACH units. First works were based on an Isothermal Differential Step (IDS) [16] and a Large Pressure Jump (LPJ) methods [17,18]. Both these approaches cannot be considered enough satisfactory as they do not allow reproduction of the isobaric adsorption phases of real ACH cycle. This severe difficulty was overcome by suggesting a Volumetric-Large Temperature Jump (V-LTJ) method [19].

In this case, the adsorbent is placed on a metal plate simulating a Heat Exchanger (HEx) fin. The plate is subjected to a quick temperature jump/drop to initiate desorption/adsorption process at almost constant pressure as it takes place in a real ACH unit. Temporal evolution of the adsorbate loading $w(t)$ is calculated from small change of the adsorptive pressure over the adsorbent. This approach has been successfully applied to study various adsorbents and operating effects [15] highlighting the benefit of considering the adsorbent and the supporting HEx as an integrated unit. In this way, a remarkable simplification of the ACH dynamic analysis was reached [15].

The main intrinsic limitation of the V-LTJ method is a small mass of adsorbent that can be tested. It is severely restricted by c.a. 0.5 g, so that only a simplest and ideal flat layer configuration of Ad-HEx can be studied [20]. This is quite far from realistic configurations of ACH units. To overcome this obstacle, a Gravimetric version of the LTJ method (G-LTJ) has recently been presented in [21] and detailed in [22]. A new experimental apparatus was specifically designed at ITAE CNR with the aim of continuous monitoring of the Ad-HEx weight evolution during isobaric ad-/desorption stages. The adsorbate loading $w(t)$ was directly measured with high reliability and accuracy through proper load cells. Total range of the sample weight measured was of 5–500 g [22].

In this paper, we take advantage of this set-up improvement to make one further step that is original and important – to apply the highly informative G-LTJ method for studying the dynamic behaviour of Ad-HEx units with much more complex and realistic configurations close to those in actual ACH units [23]. We have studied small, but representative, pieces of commercial finned flat-tube HEx filled with loose adsorbent grains. This type of Ad-HEx is considered as one of the most promising for application in ACH units [24,25]. The studied pieces of the real HEx may model, we believe, dynamic behaviour of the whole Ad-HEx. In particular, the tests are focused on better understanding the effects of the HEx geometry and adsorbent grain size. Then, the effect of the heat carrier flow rate is analysed. Quite interesting conclusions can be made when one compares the G-LTJ results for real Ad-HEx pieces with appropriate V-LTJ data for the simplest flat configuration. From a practical point of view, these results provide vital information about fundamental mechanisms of heat and mass transfer in the studied system and help a designer to build dynamically optimized ACH units.

Moreover, this study gives an idea on the degree of improvement achievable in the real ACH units, tracing useful recommendations on how to get it.

2. Experimental

2.1. Apparatus

The G-LTJ experimental apparatus was detailed elsewhere [22]. It consists of two vacuum chambers (Fig. 1). The first one is the measuring cell (volume = 12 dm^3) in which the Ad-HEx unit is located and connected both to a hydraulic heating/cooling system and to a supporting weighing unit. The latter represents the heart of the entire system. It consists of a load cell able to follow the weight evolution of samples with mass ranging between 5 and 500 g with the accuracy of 0.1 g and a time response faster than 0.1 s. The measuring chamber is connected, through the automatic