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Simulation of a closed low-pressure honeycomb adsorber for thermal energy storage

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ABSTRACT

The efficient implementation of renewable energy sources necessitates thermal energy storages. For domestic as well as industrial applications thermal energy storages based on closed adsorption are studied. Against this background, a closed low-pressure honeycomb adsorber is numerically examined in this work. The examined adsorber contains stacked layers of honeycomb blocks with rectangular channels which are separated by heat exchanger plates. Zeolite 13X and water is assumed as the adsorption pair. The focus of this work is solely on the adsorption process. The numerical model applies a one-dimensional model for the single channels of the honeycomb blocks. The one-dimensional model has been presented in a previous work of the authors. To account for transversal heat conduction in the honeycomb cross-section, the one-dimensional model equations are extended by heat source/sink terms. In addition, the mass transport equation is modified for rectangular channel flow. The results demonstrate that the heat and mass transfer and the adsorption processes are strongly coupled and can be only understood by their interaction. Regarding modelling aspects, it is found that the spatial variations of temperature and pressure as well as the local deviation from adsorption equilibrium are significant. Hence, no equilibrium assumptions should be made. Further, the minor rarefaction effect of slip should be considered. With respect to the application, the analysis yields, that the thermal power can be optimized by variation of the honeycomb geometry parameters, e.g. channel size. The local optimum is a result of the inverse dependencies of the external and internal mass transfer resistance on the channel size. Interestingly, the optimum for peak and mean power do not coincide in general. Finally, it is found that the thermal power can be controlled effectively by the inlet pressure.

1. Introduction

1.1. Motivation and subject matter

The efficient implementation of renewable energy sources necessitates both electrical and thermal energy storages (TES). For domestic as well as industrial applications, TESs based on closed adsorption are studied, e.g. [1,2]. To date most publications focus on packed-bed adsorbers with adsorbent pellets or powder filling. More recently, structured honeycomb adsorbents have been developed to improve the storage performance by reducing the heat and mass transfer resistance, e.g. [3,4]. Here, in accordance with literature, the term 'honeycomb adsorbent' refers to all extruded adsorbents independent of the shape of the channels' cross-section, e.g. [5,6]. Against this background, a closed low-pressure honeycomb adsorber is numerically examined in this work.

The one-dimensional model for a single channel of the honeycomb adsorbent has been presented and discussed for a basic adsorber set-up in [7]. Here, this model is applied and modified to simulate a more practical adsorber set-up, see Fig. 1. The insulated adsorber contains stacked layers of honeycomb blocks with rectangular channels which are separated by heat exchanger plates. In general, this set-up enhances the heat transfer between the adsorbent and the heat exchanger, thus, improving the storage performance in terms of charging and discharging duration and power. As the adsorption pair of zeolite 13X and water is often studied in applied research, e.g. [8,9], this pair is also assumed in this study. With water as adsorbate, the in- and outlet pressure of the adsorber typically lies in the range of $p_{\text{in}} \approx 10\ldots100\,\text{mbar}$, compare e.g. [10].Finally, the focus of this work is solely on the adsorption, that is the discharging process.

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Nomenclature

a	honeycomb channel height (m)
A	cross-section area (m^2)
b	honeycomb channel width (m)
c	specific heat capacity at constant volume (J/kg K)
c_p	specific heat capacity at constant pressure (J/kg K)
f	honeycomb web thickness (half) (m)
G_{P}	Poiseuille coefficient (–)
G_{T}	thermal creep coefficient (–)
Δh_{a}	heat of adsorption (J/kg)
i	honeycomb channel index ((–)
k_{a}	adsorption kinetics parameter (s^{-1})
$K_{\mathrm{I}}, \mathrm{i}$	thermal power controller parameters
Kn	Knudsen number (–)
l_{mol}	mean free path of vapour molecules (m)
L	honeycomb length (m)
m	mass (kg)
$\dot{m}$	vapour mass flow rate (kg/s)
N_{c}	number of channels in one column or row of a honeycomb block (–)
p	vapour pressure (Pa)
p_{th}	volumetric thermal power (W/m^3)
$p_{\mathrm{th,mean}}$	volumetric mean thermal power (W/m^3)
$p_{\mathrm{th,peak}}$	volumetric peak thermal power (W/m^3)
$p_{\mathrm{th,set}}$	controller set point value of volumetric thermal power (W/m^3)
R_{s}	specific gas constant of vapour (J/kg K)
t	time (s)
$\tilde{t}$	non-dimensional time $\tilde{t} := t/t_{\mathrm{tot}}$ (–)
t_{tot}	total process duration (s)
T	temperature (K)
T_{htx}	temperature of heat exchanger (K)
T_{s}	saturation temperature (K)
u	mean vapour velocity in honeycomb channel (m/s)
W	honeycomb width (m)
X	water uptake of zeolite (kg/kg)
X_{eq}	water uptake at adsorption equilibrium (kg/kg)
x, y, z	cartesian coordinates of honeycomb block (m)
$\Delta x, \Delta y, \Delta z$	knot spacing of discretization (m)

Greek symbols

γ_a, γ_b	aspect ratio of outer size of honeycomb channel cut-out to channel size (–)
$\Gamma(G_{\mathrm{P}})$	relative error of the non-dimensional mass flow)
δ	local rarefaction parameter (–)
ε	honeycomb porosity, zeolite micro-porosity (–)
ζ_{i}	parameters of slip approach of G_{P}-function (A.2) (–)
λ	heat conductivity (W/m K)
λ_{eff}	effective heat conductivity (W/m K)
ξ_{i}	fitting parameters of G_{T}-function (A.3) (–)
ρ	density (kg/m^3)
σ	volumetric heat source/sink term (W/m^3)

Subscripts

0	initial state
a	adsorbate, adsorption
c	channel
in	inlet of adsorber
max	maximum
ref	reference state
v	vapour
z	zeolite

Abbreviation

TES	thermal energy storage

1.2. Literature review

Regarding the simulation of closed low-pressure adsorbers, most publications focus on packed-bed adsorbers filled with spherical adsorbent particles [11–14] or on adsorbers with coated heat exchanger tubes, e.g. [15]. Furthermore, the field of application covers mostly heat pumps and only few publications deal with TES, e.g. [16]. Hence, the adsorbers analysed in most publications are of small scale compared to the adsorbers examined in this work and thus the limitation of the TES performance by the heat and mass transfer might be more significant.

The application of honeycomb adsorbers for TES is studied in [3,4,6]. The focus lies on the description of the manufacturing process of the honeycomb adsorbents and the physical behaviour is discussed only qualitatively or by simple models. Further, our literature review found only very few publications on the detailed modelling and simulation of zeolite honeycomb adsorbers, e.g. [17]. In summary, all publications on honeycomb adsorbers solely examine open adsorption systems and assume a stationary flow of the carrier gas. In contrast, our work applies the detailed model presented in [7] to conduct simulations of the dynamic heat and mass transfer processes in a closed low-pressure honeycomb adsorber for thermal energy storage. In addition, we account for special effects of the rarefied gas flow, such as the slip-effect and thermal creep effect, which are neglected in most publications.

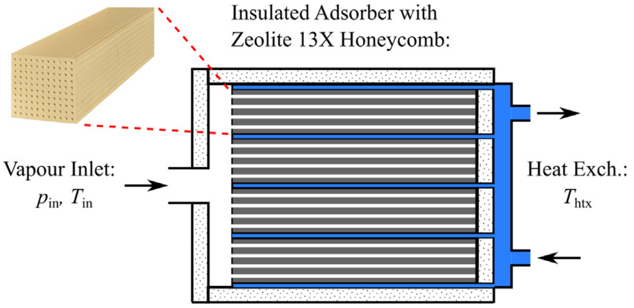

Fig. 1. Examined adsorber set-up: stacked layers of honeycomb blocks, separated by heat exchanger plates to enhance the heat transfer between the adsorbent and the heat exchanger. (Photo of honeycomb block with courtesy of B. R. Formisano.)

1.3. Objectives of study

The main objective of this study is to gain insight into the dynamic heat and mass transfer processes in a closed low-pressure honeycomb adsorber by means of numerical simulation. More specifically, the following questions regarding the modelling and the application are analysed:

Modelling:

- Is it valid to assume equilibrium in the adsorber for the temperature (isothermal), or pressure (isobaric), or the adsorption (local equilibrium of water uptake)?
- Is it necessary to take special effects of rarefied gas flow, such as the slip or thermal creep effect, into account?