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Dynamic study of methanol adsorption on activated carbon ACM-35.4 for enhancing the specific cooling power of adsorptive chillers

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HIGHLIGHTS

- Methanol adsorption dynamics on loose grains of activated carbon was studied.
- Recommendations on enhancing specific cooling power of adsorption chillers are made.
- Grain size insensitive mode of the dynamics is revealed for 0.8–4.0 mm grains.
- Dynamics is invariant in respect to ratio S/m of heat transfer area to adsorbent mass.
- The increase in S/m-ratio of the system "heat exchanger – adsorbent" is recommended.

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ABSTRACT

Lower specific cooling power (SCP) as compared to absorption and compression chillers slows down a broader application of adsorption cooling (AC) technology. In this paper, we endeavor to find out the factors dominating ad/desorption dynamics in adsorptive chillers and to make practical recommendations on optimizing the SCP. The working pair studied is "activated carbon ACM-35.4 – methanol". This carbon is the modern analog of a well-known carbon AC-35 that has been widely tested for AC units. We have experimentally examined the dynamics under a simple, but realistic configuration of a thin adsorbent bed composed of loose grains located on a flat metal plate. The effects of the adsorbent grain size (0.8–4.0 mm), bed thickness (0.8–5.6 mm), and ad/desorption temperatures are explored under conditions of isobaric stages of AC cycle. The adsorption rate appears to be mainly controlled by the heat transfer between the adsorbent bed and the heat transfer fluid. The ratio (S/m_{ad}) of the heat transfer area S to the adsorbent mass m_{ad} can be used to assess the degree of dynamic perfection of real adsorber – heat exchanger units. On the base of the main findings obtained the practical recommendations on enhancing the SCP of AC units are made.

1. Introduction

Adsorption systems of Heat Transformation (AHT) are attracting an increasing world-wide attention due to their encouraging potential for effective utilization of waste and renewable heat for cooling and heating of buildings [1,2]. Another promising application of the AHT is associated with combined cooling, heating, and power systems [3]. However, broader application of the AHT technology is slowed down by its lower specific cooling/heating power and higher investment costs as compared to absorption and compression systems [1,3]. Active current research on AHT is aimed to enhance the systems performance through improvements in adsorbents properties, use of advanced cycles, better design of the adsorption units, optimization of the operation parameters, etc [1,2,4,5–7]. A lot of efforts have been dedicated to the specific power enhancement [4,5,7]. The specific power is greatly affected by the organization of heat and mass transfer in an "adsorber – heat exchanger" (Ad-HEx) unit.

AC cycles based on methanol as refrigerant are considered promising for both air conditioning and ice making due to high operating pressure and low freezing point of methanol [8–11]. Various activated carbons exhibit a high methanol uptake under typical conditions of AC cycles [12–15]. The performance of AC cycles that utilize "activated carbon fibers – methanol" working pair was studied in [10]. As compared to "silica gel – water" pair, this pair shows better performance at low chilled fluid temperature at the same inlet temperature difference between cooling and chilled fluids. The possibility to combine heating and air-conditioning of a building of 100 m^2 area using two adsorbers filled with 20 kg of activated carbon AC-35 was demonstrated in [16]. A cooling Coefficient of Performance (COP) varied from 0.12 to 0.6 and cooling capacity changed from 1.0 to 4.5 kW during a day. A

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Nomenclature

A	heat flux (W)
COP	Coefficient of Performance
c_p	specific heat (J/gK)
D_{gr}	grain diameter (mm)
l	layer thickness (mm)
d_{av}	average pore diameter (nm)
ΔF_{ads}	adsorption potential (kJ g^{-1})
ΔH_{ads}	adsorption enthalpy (kJ g^{-1})
h	heat transfer coefficient between the bed and the support (W m^{-2} K^{-1})
L	latent heat of vaporization (kJ mol^{-1})
M	molar mass (g)
m	mass (g)
N	layers number
P	pressure (mbar)
Q	heat (J)
q	conversion
R	universal gas constant (kJ mol^{-1} K^{-1})
R_0	initial sorption rate (gg^{-1} s^{-1})
S	heat transfer surface (m^2)
S_{sp}	specific surface area (m^2 g^{-1})
SCP	specific cooling power (W kg^{-1})
T	temperature (K)
T	time (s)
U	global heat transfer coefficient (W m^{-2} K^{-1})
V	volume (m^3)
V_p	pore volume (cm^3 g^{-1})
W_{max}	maximum cooling power (W kg^{-1})
w	mass of methanol adsorbed (gg^{-1})

Greek symbols

λ	heat conductivity (W m^{-1} K^{-1})
τ	characteristic time (s)

Subscripts

ad	adsorbent
ads	adsorption
b	adsorbent bed
des	desorption
ev	evaporation
HEx	heat exchanger
reg	regeneration
v	vapor

two-bed adsorptive ice-making machine that operated with a heat and mass recovery and used "activated carbon – methanol" pair was installed for onboard refrigeration in fishing boats [17]. This unit produced 18–20 kg of flake ice per hour at 266 K. Unfortunately, for the mentioned units the SCP, that characterizes the dynamic efficiency of AC cycles, remained quite low and did not exceed 20–100 W kg^{-1} of the adsorbent [9,16,17].

The main goal of this work was a comprehensive study of the dynamics of methanol adsorption under typical conditions of isobaric stages of AC cycle. We examined a simple Ad-HEx configuration, namely, an adsorbent bed composed of loose grains located on a flat metal plate. Despite its simplicity this configuration is rather usable in both prototypes and commercial AC units [18]. The plate was subjected to a temperature drop/jump as it takes place in real AC machines. The adsorbent studied was an activated carbon ACM-35.4 that is the modern analog of a well-known activated carbon AC-35 widely tested in AC units [13,14,19]. In this paper, we endeavor to find out the factors dominating ad/ desorption dynamics in adsorptive chillers. For enhancing the SCP we try to understand what is the optimum adsorbent mass per 1 m^2 of a HEx and what is the optimum size of adsorbent grains.

Appropriate recommendations on optimizing the configuration of Ad-HEx unit are made to bridge the gaps between research, development and implementation of AC units. This would greatly help in the optimal use of renewable and waste heat sources.

2. Materials and methods

Activated carbon ACM-35.4 with the average pore size $d_{av} = 2.3$ nm, the specific surface area $S_{sp} = 1200$ m^2 g^{-1}, and the specific pore volume $V_p = 0.69$ cm^3 g^{-1} produced by CECA Arkema group was studied. It is characterized by advanced microporous structure leading to a maximal methanol sorption of 0.38 gg^{-1}. The isotherms of methanol adsorption on ACM-35.4 and common AC-35 [13] nearly coincide (Fig. 1). The carbon was milled and sieved to get the following fractions: $D_{gr} = 0.8–0.9$, 1.0–1.25, 1.6–1.8, 2.5–2.8, and 4.0–4.1 mm.

The methanol adsorption dynamics was studied by a Large Temperature Jump (LTJ) method that imitated typical conditions of isobaric stages (4–1) and (2–4) of AC cycle (Fig. 2) [20]. The experimental rig contained three main parts: a measuring cell with the studied adsorbent, a buffering vessel and an evaporator with liquid methanol (Fig. 3). Loose adsorbent grains were placed on the metal support as one, two or more (N) layers. To arrange different number N of layers a fixed mass of the adsorbent ($m_{ad} = 500$ mg) was located on the support inside a thin ring made of parafilm (Fig. 4). The ring was used to limit a contact surface area S between the adsorbent and the metal support. Temperature of the support may be quickly varied by using a heat carrier circuit coupled by a three-way valve (3WV) to circulating thermal baths (Fig. 3).

The temperature of the buffering vessel as well as of all connecting pipelines was maintained at 50 ± 0.5 °C by using an air bath oven. Methanol vapor was generated by an evaporator with a cooling jacket. The vapor pressure was measured by an absolute pressure transducer Barocel® 600 with an accuracy of ±0.15%. After evacuation of the experimental rig to a residual pressure of 0.01–0.02 mbar, the buffering vessel and the measuring cell were

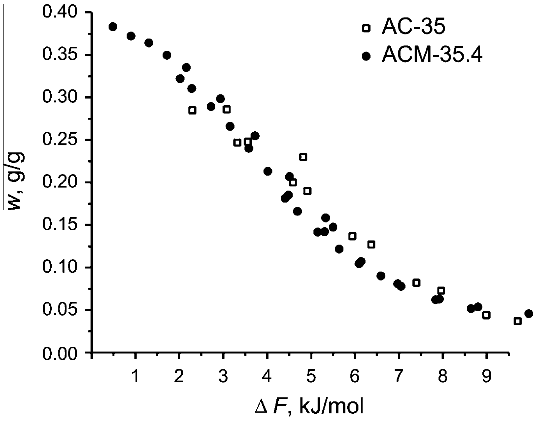

Fig. 1. Isotherms of methanol adsorption on ACM-35.4 and common AC-35.