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Influence of new adsorbents with isotherm Type V on performance of an adsorption heat pump

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A R T I C L E I N F O

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The working pair is one of the main influencing parameter on performance of an adsorption heat pump (AHP). Researchers started to synthesize different adsorbents in order to improve the adsorption rate. Even the adsorption rate could seem very well, the new adsorbent could not be suitable for an AHP for given conditions. In this context, the effect of new adsorbent materials with isotherm Type V on adsorption-desorption processes of an unconsolidated adsorbent bed works for refrigeration are investigated. The adsorbate is taken as water. Type V isotherm equations for each adsorbent are predicted and the influence on the performance is analyzed. The constants in the equation that simulate the isotherm shape are found. The average temperature/concentration in the rectangular bed during the adsorption/desorption processes are plotted for different novel adsorbents; FAM-Z01, FAM-Z02, MIL101@GO5, and NH2-MIL-125(Ti). The performed numerical solutions for the case which is taken into account for this paper (evaporator temperature and bed heating temperature are 2 °C and 77.5 °C) showed that, MIL101(Cr)@GO5 has the best Specific Cooling Power for the volume of the bed which is 21.13 kJ/kg$_a$ but has worst COP as 1.20. FAM-Z01 has 53.85 kJ/h evaporator capacity where this value is the best for the case.

1. Introduction

In recent years, the products that do not use fossil fuels get importance in order to reduce the impact on the environment and energy consumption due to industrial development. Therefore, researchers focus on waste water and industrial waste treatments [1–9]. Sorption of pollutants and using of adsorbents for removing of hazardous dyes [10–18] get importance by the researchers. Some applications directly affect the industrial impact which one of them is air conditioning application. Heating and cooling systems are widely used in industry and comfort applications. Improvement of these systems is an important research area due to the growing need of comfort conditions. Reducing the environmental damage and the limitation of the fossil energy sources has increased attentions on the use of renewable and waste heat energy sources.

Heat pumps are one of the most common devices used for saving energy. Heat pumps are classified into two groups as mechanically and thermally driven heat pumps. Adsorption heat pump (AHP) which is a kind of thermal heat pump is a promising system due to its ability for recovering heat from the thermal source at low temperature levels and providing cooling and/or heating effects. It has advantages such as being environmental friendly, having no vibration and lower operation costs.

A reason of having low cooling efficiency of an adsorption heat pump is the slow heat and mass transfer in adsorbent bed. Many researchers focus on accelerating the heat and mass transfer in the adsorbent bed. Ilis et al. [19–21] and Demir et al. [22] focus on improvement of heat and mass transfer inside of the adsorbent bed by developing numerical investigations. There are many methods for accelerating the heat and mass transfer in an adsorbent bed such as use of fins or metal additives [20,22–25]. On the other hand, new adsorbents are started to be introduced to the literature not only for heat pumps but also for other sorption applications [26–36]. These new developed adsorbents are new ways to improve the performance of the adsorption heat pumps. Silica-gel and zeolites can be defined as common adsorbents for the adsorption heat pumps. Many types of these materials were improved like SWS-1L by adding calcium chloride to mesoporous silica gel [37] or synthesized zeolite like zeolite 5A or 13X. Also new type of zeolite based adsorbent, FAM, is one of the new adsorbents for the heat pumps. FAM Z01 and Z02 were firstly introduced by

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Nomenclature

C_p	specific heat of adsorbent, J/Kg K
D_{eff}	effective diffusivity, m^2/s
D_o	reference diffusivity, m^2/s
K_{app}	apparent permeability, m^2
m	mass, kg
P	pressure, kPa
r_p	radius of adsorbent granule, m
T	temperature, K
t	time, sec
W	local adsorbate concentration, kg_l/kg_s

Greek symbols

ρ	density, kg/m^3
ΔH_{ads}	heat of adsorption, J/kg
ϕ	porosity
λ	thermal conductivity, W/mK
μ	viscosity of fluid (Nsm^{-2})

Subscriptions

eff	effective
eva	evaporator
v	vapor
l	adsorbate
a	adsorbent
sat	saturation
∞	equilibrium

Kakiuchi et al. [38,39] and concentration limit for Z01 and Z02 is given up to 0.2 and 0.3 kg/kg, respectively. Goldsworthy [40] studied on isotherms of aluminophosphate based zeolite which have been developed by Mitsubishi Plastics named as AQSOA-Z05 [41].

The isotherm shapes of these new developed materials are Type IV or V. This type of isotherm illustrates that, the concentration inside of the adsorbent increases rapidly to equilibrium humidity level. Ali and Chakraborty [42] also analyzed the AQSOA-Z02 type adsorbent and silica gel in order to decide the best adsorbents for cooling and desalination. They simulated the transient behaviors of cooling + desalination and they calculated the specific cooling power (SCP), coefficient of performance (COP) of the system. Girnik and Aristov [43] also studied on AQSOA-Z02-water pair. The aim of their study is to analyze how a number of the adsorbent layers, grain size, and cycle boundary temperatures affect the dynamics of the water adsorption. One of the other novel adsorbent is metal organic framework (MOF). MOFs consist of metal ions and can have one, two or three dimensional structures. Due to high level of water vapor adsorption capacity, MOFs can be considered as novel adsorbent for refrigeration and drying processes. Many researchers and groups [44,45] tested different types of MOFs such as MIL-100, MIL-101 and found that the water vapor capacities of these materials are around 0.8–1.28 g/g. In the study of Yan et al. [46] MIL-101@GO was synthesized by loading the graphene oxide (GO) to improve the high water vapor capacity. They worked on the adsorption isotherm and kinetics of water vapor over this new material. They also measured the diffusion coefficient of water vapor on MIL-101@GO composite. Another study with MIL-101 is performed by Liejun et al. [47]. The working pair in this paper is MIL-101/isobutane. Adsorption isotherms and dynamics are discussed in their study. MIL-125 is another novel composite for the AHP. MIL-125 is a Ti-incorporated MOF structure. If MIL-125 is functionalized with amine it is called as NH2-MIL-125. Kim et al. [48] worked on MIL-125 and NH2-MIL-125. Their stabilities against different solvents were evaluated and the CO_2 and water vapor adsorption behaviors were measured. In the study of McNamara et al. [49], addition to MIL 125, MIL-47 was one of their MOF. Kinetic data for the oxidation of heterocyclic sulfur compounds catalyzed by MIL-47 and MIL-125 was found in their study. Gordeeva et al. [50] studied on water adsorption capability of NH2-MIL-125. Specific surface area, total, and micro-pore volumes of the composite were measured. Isobars of water adsorption and desorption on NH2-MIL-125 at vapor pressure 0.7, 1.2, 2.4, 3.7 and 5.6 kPa were plotted. Isosteric enthalpy of water adsorption on NH2-MIL-125 was also analyzed.

In this study, the use of new novel adsorbents such as FAM Z series and MIL-101, 125 in the adsorbent bed for enhancement of heat and mass transfer through four processes of an adsorption heat pump cycle is analyzed in order to understand if these novel composites are suitable for real refrigeration applications of AHP. The results were compared with the silica gel RD (Fuji Silysia Co.) type adsorbent. The isotherm equations for each composite were introduced to the literature for the first time. The conservation of mass and energy equations, Linear Drive Force (LDF) model and Darcy Law equations are solved to find temperature, water concentration, water vapor velocity and pressure in the adsorbent bed for entire cycle for each adsorbent. The ideal gas equation is used to relate the water vapor pressure with its density and temperature. The Coefficient of Performance (COP) and Specific Cooling Power (SCP) of the considered adsorption refrigeration system are found for each novel adsorbent with isotherm Type V and compared with silica gel RD with isotherm Type I. The results showed that the proper adsorbent should be analyzed for the considered adsorbent bed design and the expectations from the system should be established very well. FAM Z01 and NH2-MIL-125(Ti) give the best COP results for the considered refrigeration problem taken into account in this study.

2. The considered problem

Fig. 1 shows the schematic view of the analyzed rectangular adsorbent bed filled with adsorbent granules. The radius of adsorbent particle is 0.01 mm. The adsorbent bed is cooled and heated from both the upper and the bottom sides. The adsorptive (water vapor) enters from the left side of the bed and exists from the right side. At beginning of the adsorption process all valves are closed. During the adsorption process, the valve 1 is opened and allows the vapor to flow inside of the bed while the bed is cooled from the upper and bottom parts. Then valve 1 is closed and the bed is heated from the upper surfaces, then the valve 2 is opened during

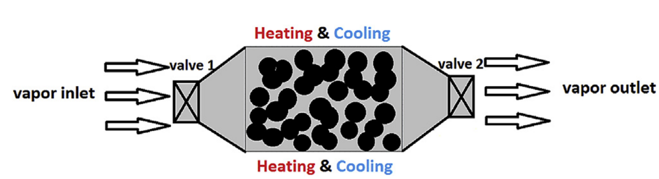

Fig. 1. Schematic view of the adsorbent bed.