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Performance of adsorbent-embedded heat exchangers using binder-coating method

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ABSTRACT

The performance of adsorption (AD) chillers or desalination cycles is dictated by the rates of heat and mass transfer of adsorbate in adsorbent-packed beds. Conventional granular-adsorbent, packed in fin-tube heat exchangers, suffered from poor heat transfer in heating (desorption) or cooling (adsorption) processes of the batch-operated cycles, with undesirable performance parameters such as higher footprint of plants, low coefficient of performance (COP) of AD cycles and higher capital cost of the machines. The motivation of present work is to mitigate the heat and mass "bottlenecks" of fin-tube heat exchangers by using a powdered-adsorbent cum binder coated onto the fin surfaces of exchangers. Suitable adsorbent–binder pairs have been identified for the silica gel adsorbent with pore surface areas up to 680 m^2/g and pore diameters less than 6 nm. The parent silica gel remains largely unaffected despite being pulverized into fine particles of 100 μm, and yet maintaining its water uptake characteristics. The paper presents an experimental study on the selection and testing processes to achieve high efficacy of adsorbent–binder coated exchangers. The test results indicate 3.4–4.6 folds improvement in heat transfer rates over the conventional granular-packed method, resulting a faster rate of water uptake by 1.5–2 times on the suitable silica gel type.

1. Introduction

In adsorption chillers and desalination plants, the adsorption and desorption beds comprise usually the fin-tube heat exchangers [1–3] where granular adsorbent are packed compactly in between the mesh-wrapped spaces of fins that facilitates the vapor uptake or desorb during the successive cooling and heating processes. Although the fin-tube exchangers are easy to fabricate, they suffer high overall heat transfer resistances due to poor point-contacts of granular adsorbent to the fins, decreasing the performance of adsorption/desorption processes [4]. The lower heat transfer efficiency of adsorbers/desorbers result in inferior temperature gradients across the metal fins to the adsorbent [5], affecting the adsorption capacity of adsorbent and the cooling capacity of chillers, etc.

From literature, much effort to improve the heat transfer across the adsorbents and exchangers have been attempted: One approach mixed the adsorbents with high thermal conductivity additives to achieve a better physical contact among solid particles. Guilleminot et al. [6] embedded zeolite particles into a metallic foam to improve conduction resistances but at the expense of mass transfer resistances. Tatlier and Erdem-Şenatalar [7] synthesized zeolite 4A with suitable metal formwork to achieve optimal thicknesses. Hu et al. [8] and Wang et al. [9] examined a high thermal conductivity polymer, polyaniline, on zeolite to improve heat conductivity by two to three folds. Similar approaches were tried by Eun et al. [10], adding natural expandable graphite into silica gel powder and compacted into composite blocks to give one order higher thermal conductivity. Attempts to increase heat transfer by using binder as fillers within the interspaces of adsorbent solids include Yanagi and Ino [11], where they tested a composite silica gel (4.3 wt% of graphite, 86.4% of silica gel and binder) heat exchanger, van Heyden et al. [12] conducted experiments with a coated alumina-phosphate (AlPO-18) nano-crystalline onto a pre-etched aluminum layer with polyvinyl alcohol (PVA) as binder, Chang et al. [13] to coat the silica gel onto stainless steel fins and Basile et al. [14] studied a composite structure using natural zeolite with the PTFE binder: They concluded that the adsorption kinetics of composite adsorbent is dependent on the thickness of adsorbent coating, and the thermal resistances are lower across the heat exchangers. Pino et al. [15] studied two types of binders (PTFE and aluminum hydroxide) and additives (SiC, Si_3N_4, and graphite)

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to zeolite 4A, and reported that PTFE with additives had insignificant effect but the $Al(OH)_3$ binder on the composite sample showed significant increase in the thermal conductivity.

In the present work, a suitable binder is proposed to bind the silica gel power for the assessment of overall heat transfer rates in a tube-fin heat exchangers. The powered silica gel-binder formed a thin layer on the surfaces of metal fins, eliminating the need for wire mesh used to wrap around the exchangers. Two types of powdered silica gel were used: (i) type 3A with 200 μm average diameters and (ii) type RD at 70 μm average diameter. The water adsorption capacity of the silica gels is understood through isotherm measurements. The baseline comparison is the conventional meshed fin-tube heat exchangers with the granular silica gel at 1.06 mm average diameter.

2. Binder selection

2.1. Adsorbents

The present section presents a method of selection of binders for silica gel–water pair, an inexpensive alternative to the zeolite–water pair for adsorption chillers, desalination plants and dehumidifiers. The general thermo-physical properties of powdered silica gels, namely type 3A and type RD powder, are depicted in Table 1 [16] whilst the granular silica gel (type RD granules) is the baseline case.

2.2. Binder comparison

As adsorption is a surface phenomenon occurring on the solid–gas interfaces [17–20], the uptake of gas molecules is dependent on the pore surface area of the meso-porous adsorbent [21]. Incorporating binder materials onto the inter-particle interfaces may have two effects on the adsorbent performance. Firstly, the binder fills inter-particle spaces to reduce thermal resistance with enhanced physical contact, and secondly, in the worst situation, the flow of vapor into the micro pores of adsorbent may be impeded due to surface area coverage, reducing the vapor uptake. A suitable binder must fulfil the following criteria to achieve an optimal balance between the thermal heat and the sorption mass transport: (i) it possesses good adhesive ability between adsorbent particles and supporting metal fins, as well as among the adsorbent solids, (ii) improves the contact heat transfer between the adsorbent and metal fins, (iii) impose null or positive influence the adsorbate uptake, (iv) remains chemically inert to the adsorbent–adsorbate pair, (v) maintains a high durability.

Experiments were conducted on seven types of binder mixed with silica gel type 3A, namely, epoxy, polyvinyl alcohol (PVA), corn-flour, hydroxyethyl cellulose (HEC), gelatin, bentonite, and sepiolite. The former five binders used are organic-based whilst the latter two are of inorganic type. In each test, samples were made by mixing in a adsorbent–binder mass ratio of 1:10; stirred thoroughly as a mixture in distilled water to achieve an uniform distribution prior to coating it onto 20 × 20 × 0.4 mm aluminum laminas. The coated samples were first dried at room temperature for 24 h, and followed by curing in an oven at 120 °C for 12 h. The cured samples were tested for BET surface area using the AUTOSORB-1 (Quantachrome Instruments) analyser [22], using nitrogen sorption procedure at assorted pressures and constant temperature conditions [23].

The results of the binder performance are tabulated in Table 2. Poor adhesive ability onto the fin surface is observed on the inorganic binders, namely bentonite and sepiolite. However, the organic binders exhibit better binding strength of silica gel powder onto the surfaces. The epoxy shows a low BET surface area and has a "browning" tendency after curing. Also the gelatin and PVA samples have the peel-off tendency across the binder-adsorbent weight ratios. The tests show that the HEC-adsorbent samples were found to be suitable for the silica gel on metal fins. In addition, the nitrogen sorption test on the binder HEC alone at 77 K using AUTOSORB-1 analyzer shows that it has a minor sorption capacity, as summarized in Table 3 [24]. The HTC has a softening temperature of 140 °C, yet most desorption processes of adsorption cycles are operated below 90 °C.

2.3. Optimum binder ratio

Fig. 1 shows the effect of silica gel-binder weight percentages of the adsorbent, varying from 1.67%, 3.33%, 6.67% and 10% of the silica gel are compared. The BET surface area and porous volume are observed to peak at 3.3 wt% ratio, achieving 507 m^2/g and 0.334 ml/g. As seen in Fig. 2, the reduction in its micro-pore size volume, expressed in Dubinin–Astakhov model, is found to be the lowest.

Table 1
Thermophysical properties of silica gel type 3A, type RD powder and granule.

Properties	Type 3A	Type RD	
		(Powder)	(Granule)
Average particle diameter [mm]	0.2	0.07	1.06
BET surface area [m^2/g]	680	573	557
Porous volume [ml/g]	0.47	0.39	0.35
Apparent density [kg/m^3]	770	800	800
Thermal conductivity [W/m K]	0.174	0.198	0.198
Specific heat capacity [kJ/kg K]	0.921	0.921	0.921
Mesh size	30–200	>100	10–20

Table 2
Comparison of various binders on the silica gel and metal fin binding. The mixing ratio of all binders to the adsorbent is fixed at 1:10.

Binder name	Type	Adhesive characteristics	BET surface area [m^2]
Epoxy	Organic	• Good between silica gel and fins, as well as on silica gel solids • Browning color after curing	48.07
Polyvinyl alcohol (PVA)	Organic	• Good on silica gel solids; • Fair between silica gel and fins, some samples peer off from fins	334.7
Corn flour	Organic	• Good between silica gel and fins, as well as on silica gel solids • Binding degrades with time	397.1
Hydroxyethyl cellulose (HEC)	Organic	• Good between silica gel and fins, as well as on silica gel solids	384.6
Gelatin	Organic	• Good on silica gel solids; • Fair between silica gel and fins; some samples peer off from fins	286.2
Bentonite	Inorganic	• Poor between silica gel and fins, as well as among silica gel solids	–
Sepiolite	Inorganic	• Poor between silica gel and fins, as well as among silica gel solids	–

Table 3
Properties of hydroxyethyl cellulose (HEC).

Properties	Value
BET surface area [m^2/g]	1.762
Porous volume [ml/g]	0.031
Apparent density [kg/m^3]	600
Specific heat capacity [kJ/kg K]	~3.851
Softening temperature [°C]	>140 °C
Decomposition temperature [°C]	205 °C