Effect of catalyst and substrate on the moisture diffusivity of silica-aerogel-coated metal foams

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ABSTRACT

Silica aerogel desiccants have good adsorption and desorption characteristics and commonly are deployed on metallic or non-metallic substrates as thin coatings in typical dehumidifying applications. The dehumidifying performance of desiccant coated on substrates often depends on the micro-structure of desiccants, as well as on the characteristics of substrates, such as surface area. The current study focuses on the preparation and adsorption/desorption performance evaluation of various types of silica aerogel coatings on different metal foam substrates. The silica aerogel coated metal foam samples have been prepared by dip coating process using different basic and acidic catalysts, followed by the super-critical drying. The microstructures of aerogel coating obtained by scanning electron microscopy, are compared to porous structures of solid desiccant blocks prepared using the same method (catalyst). A new automatic dynamic vapor sorption method is used to determine the mass diffusion coefficient of silica aerogel coated foam samples. SEM image analysis is used to determine the geometrical parameters (pore diameter, ligament diameter) of coated and uncoated foams of 5, 10 and 20 PPI for data reduction. The impact of substrate type and microstructure of the coating, which depends on the catalyst used in sol–gel process on the mass diffusivity, has been evaluated. The results of this study can be used in the development and performance evaluation of various dehumidification applications containing silica aerogels deployed as thin coatings.

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1. Introduction

Because of the importance of energy efficiency in the built environment, there is significant interest in separating the sensible and latent loads when conditioning air for human comfort. Separating the sensible and latent loads offers significant potential in energy savings and provides opportunities for improved control of temperature and humidity. Many recent studies of dehumidification systems have focused on the development of solid adsorbent systems that can provide improved sorption capacity and higher mass and heat transfer rates, as well as favorable equilibrium isotherms [1–3]. Adsorption systems with improved performance result in substantial decreases in the initial and operating costs and in some cases make such dehumidification systems attractive alternatives to existing vapor compression systems for cooling and dehumidification. In general, the salt adsorbents, such as calcium chloride, have better moisture absorbing capacity than the organic

adsorbents, such as silica gel, but deliquescence occurs on the surface of calcium chloride granules beyond a certain adsorption level and a hydrate solution is formed. This behavior limits the effectiveness of salt desiccants [3]. In order to overcome this problem, desiccant materials based on silica aerogel have become an attractive alternative to the existing salt-based adsorbents. They have been used as a high-performance desiccant to remove water vapor from humid ventilation air for buildings [4]. There is no chemical reaction involved during adsorption and desorption. Even when saturated with water vapor, silica gel still has a dry appearance with its geometry unchanged, which is an advantage over liquid desiccant systems.

The solid desiccant can be deployed by coating a solid substrate. The characteristics of the substrate, such as surface area and thermal conductivity, affect the moisture removal performance considerably. Therefore, an appropriate dehumidification performance evaluation of the desiccant coated on the substrate is important. One potential candidate for a substrate material is metal foam. There has been considerable interest in establishing the thermal–hydraulic performance of metal foams when used as a heat exchanger. Despite manufacturing and implementation

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Nomenclature

D	effective diffusion coefficient (m²/s)	ρ	moisture density (kg/m³)
r_1	metal foam ligament diameter before coating (mm)	t	time (s)
r_2	metal foam ligament diameter after coating (mm)		

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issues, these materials hold promise as both heat exchangers and heat sinks [5–8]. The open porosity, low relative density, high thermal conductivity, large surface area per unit volume, and the ability to enhance fluid mixing can make metal foam thermal management devices efficient, compact, and light-weight. Two major advantages of using metal foams as substrates are the large surface area per unit volume and a thermal conductivity higher than that of the desiccant. A relatively large quantity of silica aerogel can be deployed as thin coating on the foam, and the higher thermal conductivity of the foam assists in removing the heat of adsorption and can provide heat for desorption. A proposed configuration consisting of metal foam coated with silica aerogel is shown in Fig. 1 [9]. The current study is focused on evaluating the dehumidification performance of aerogel-coated metal foams.

The adsorption and desorption characteristics of different silica gel coatings may vary because of different manufacturing procedures [3]. Although silica gel is frequently used as a desiccant, the transport of heat and moisture within the pores of silica gel particles is complex and research is ongoing. Comprehensive experimental studies of the physicochemical properties and some research applications of the organic and salt-based adsorbents have been reported by Aristov et al. [1] and Zhang et al. [3]. These studies show that silica-aerogel-based adsorbents have a higher adsorption capacity and can be regenerated with a lower temperature than the other commercially available desiccants, such as activated carbon. Despite such promising properties, conclusions as to the feasibility of these materials for sorption systems can only be drawn after dynamic analysis of the adsorption and desorption performance of the silica aerogel coated on the substrate under realistic operating conditions. The capacity of a porous adsorbent solid in adsorption of an adsorbate gas is determined by the adsorption isotherm, and the mass diffusivity affects the adsorption rate. However, the dynamic adsorption properties of adsorbents with different microstructures have not been widely reported, and this is especially true for the solid side mass diffusivity of aerogels coated on a metal foam surfaces. The main objective of the present work is to investigate the dynamic properties and desiccant mass diffusivity of different silica aerogels coated on metal foams.

1.1. Preparation of silica aerogel coated samples

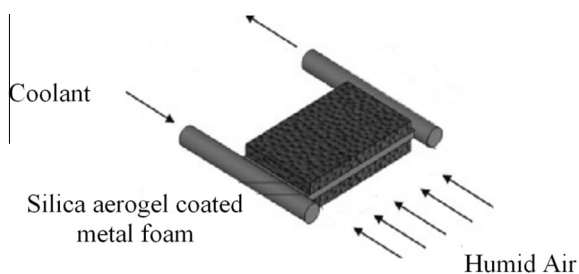The sol–gel process is the most common method for the preparation of aerogels, during which the hydrolysis of silicon alkoxides generates intermediate species, and these species then undergo a stepwise poly-condensation reaction to form a three-dimensional gel network. The secondary step is the supercritical drying of the gel, which involves drying above the critical temperature and pressure of the solvent present in the pores of gel.

The sol–gel technique has been recently reviewed by a number of investigators [10–21]. Brinker and Scherer [22] described the sol–gel process and how it is affected by a number of parameters, including the way hydrolysis and condensation are carried out, the pH of the catalyst used, and the temperature and pressure at which the sol–gel process is performed. Their work also described the effects of ageing and possible applications of different types of aerogels. Husing and Schubert [23] provided a detail review of the sol–gel process including the different options for precursor groups and the drying processes for wet gel under ambient and super-critical conditions. They found that the characteristics of the resulting aerogels depended on the manufacturing methods. Frenzer and Maier [24] studied the use of sol–gel process for amorphous porous materials in terms of preparation, characterization, and application. They stated that there was huge potential for the tailoring of chemical composition, microstructure, porosity, and surface properties by changing the manufacturing procedure. A large variety of precursors, additives, modifiers, solvents, catalysts, and post treatment conditions provide ample fine-tuning options for the characteristics of porous media. They concluded that, although silica aerogels is an amorphous porous material, the properties are quite similar to those commonly associated with well-defined crystalline solids.

Despite significant advances in technologies based on sol–gel thin film process, there has been relatively little effort directed toward understanding the fundamentals of sol–gel coating processes. Dip coating is one way to deposit a thin layer of a desiccant on a substrate surface. In dip coating, the substrate is normally withdrawn vertically from the coating bath at a constant speed [25]. The moving substrate pulls liquid out of the bath, retaining a liquid layer, the thickness of which depends on substrate surface condition, speed of withdrawal, liquid properties, and ambient conditions. Since the solvent is evaporating and draining, the liquid film acquires a wedge-like shape that terminates at a well-defined drying line. When the receding drying line velocity equals the withdrawal speed, the process is in steady state with respect to the liquid bath surface.

The hydrodynamic factors in dip coating (pure liquids, ignoring evaporation) were first calculated correctly by Landau and Levich [26] and later were generalized by Wilson [27]. Scriven [28] conducted a review of the progress of the dip coating process and stated that the thickness of the deposited film is related to the position of the streamline dividing the upward and downward moving layers. He found that the competition between six forces in the film deposition region governed the film thickness and position of the streamline. These forces included (1) viscous drag upward on the liquid by the moving substrate; (2) force of gravity; (3) resultant force of surface tension in the concavely shaped meniscus; (4) inertial force of the boundary layer liquid arriving at the deposition region; (5) surface tension gradient; and (6) the disjoining (or conjoining) pressure (important for films less than 1 micron thick).

Fig. 1. A configuration for aerogel coated metal foam dehumidification device.