



Performance characteristics of thin-multilayer activated alumina bed



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HIGHLIGHTS

- Activated alumina has large mass transfer characteristics in hot very humid zones.
- Activated alumina adsorption rate is doubled as inlet air RH rises from 50% to 80%.
- Long cycle durations reach high COP but with high moisture content of exit air.
- Short cycle durations attain uniform moisture content of exit air but with low COP.
- Activated alumina has better COP and faster dynamic response than silica gel.

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ABSTRACT

This paper reports the experimental mass transfer characteristics of thin-multilayer activated alumina bed that is used in desiccant-cooling systems working in humid and very humid climates, during adsorption and regeneration processes. These characteristics include transient response, adsorption and desorption rates, mass transfer coefficients and latent COP. Effects of dry bulb temperature and humidity of ambient air on single, double or triple-layers bed are experimentally investigated. In addition, effects of cycle duration on latent COP and adsorption process are considered. The experimental results proved that long cycle duration achieves high latent COP but with large moisture content of exit air while short cycle duration accomplishes uniform moisture content of exit air but with lower latent COP. The mass transfer characteristics of activated alumina beds are superior for hot very humid climates (high ambient temperature and relative humidity) with more uniform relative humidity of exit air being achieved by triple-layers bed. The comparison between activated alumina and silica gel, under the same conditions, revealed that activated alumina achieves higher COP, particularly for short cycle duration.

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1. Introduction

Dehumidification process using desiccant materials is widely used in industrial processes including drying of air, natural gas and other gases, drying and pharmaceutical industry, etc. [1]. Also, desiccant-cooling systems are proper alternative to conventional systems, particularly in humid climates [2] where the compression air conditioning might be an ineffective and costly technique [2,3]. In such applications the air is dehumidified by sorption using a desiccant bed (adsorption dehumidification) instead of cooling the air below its dew point to condense the moisture. In most cases, the conventional cooling-based dehumidification requires overcooling and is limited by the water freezing phenomenon occurring at 0 °C. On the other hand, the desiccant-cooling is

capable to treat air with dew point of −40 °C [4]. However, as the desiccant adsorbs moisture from air, it becomes saturated and it must be regenerated or reactivated through a process in which moisture is driven off (desorbed) by heat from an energy source such as electricity, waste heat, natural gas, or solar energy [5–7]. Thus, desiccant beds experience cycles of successive adsorption and regeneration processes.

Recently, focus has been paid to various desiccant-cooling systems and their characteristics are extensively reviewed [8–13,15,14]. Also, their technical and economical feasibility in various climates are demonstrated [13,15–18]. However, the main component of desiccant-cooling systems is the desiccant bed where many configurations such as liquid spray bed, packed bed, multiple vertical beds and rotating wheels or honeycombs [19–22] are practiced using solid or liquid desiccant materials [23–25].

Zouaoui et al. [8] reviewed the topic of solid desiccant and reported that the treated air is dehumidified in most cases through

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Nomenclature

A	duct cross section area (m ²)	T	temperature (°C)
Bi	Biot number for heat transfer (-)	V	air velocity (m/s)
Bi _m	Biot number for mass transfer, (-)	w	humidity ratio (g _w /kg _a)
COP	coefficient of performance (-)	Δw	difference between humidity ratios of inlet and exit air (g _{wv} /kg _a)
c _p	specific heat of air (kJ/kg K)	ρ	air density (kg/m ³)
E/m	energy required to dehumidify 1 kg of water vapor from humid air (kJ/kg)		
E _r	rate of thermal energy input during regeneration mode (kW)	<i>Subscripts</i>	
h _{fg}	latent heat for condensation (kJ/kg)	a	air
\dot{m}	mass flow rate of air (kg/s)	d	adsorption dehumidification
\dot{m}_w	mass flow rate of water vapor (kg/s)	des	desiccant material
\dot{M}_w	adsorption/desorption rate (kg/h)	i	inlet
p	pressure (Pa)	o	out, exit
P _{fan}	fan power (kW)	r	regeneration
Q	rate of thermal energy transferred between desiccant material and air (kW)	s	saturation
RH	relative humidity (%)	w	water vapor
t	time or cycle duration (s)	ws	saturated water vapor

a rotating desiccant wheel that achieves more uniform humidity in process air. On the other hand, thick-desiccant beds that are commonly used in industrial processes can deal with a great amount of moisture in process air. However, the present work proposes the use of thin-multilayer activated alumina bed in desiccant-cooling systems. The proposed bed is economically viable and incorporates the benefits of both fixed bed and rotating wheel as it functions without motor with less energy and noise. In the same time, the thin-multilayer bed has fast response and uniform humidity of process air. Also, thin-multilayer bed experiences low pressure drop and consequently requires small pumping power to drive the process air through. The stated advantages of thin-multilayer bed demonstrate its potential in desiccant-cooling system as it affords a cost effective technique that handles the latent load of air conditioning process. It is to be stated that the uniform humidity of exit air from thin-multilayer bed depends, to great extent, on the cycle duration that needs to be studied along with the desiccant mass as stated by Zouaoui et al. [8].

Activated alumina was not tested before in thin or multilayer or thin-multilayer beds as silica gel has been the mainstay desiccant agent in industrial and laboratory use for many years. Development of specialized and customized alumina targeted to specific applications has enhanced its properties [26,27]. Activated alumina has become cost-effective solutions for many pressing environmental problems. In practice, activated alumina surpasses silica gel in performance by offering superior amphoteric properties; greater stability over a broad pH range; no degradation at either high pressure or high temperature setting; and strong affinity for halides [28]. Moreover, activated alumina is resistant to thermal shock and abrasion and does not shrink, swell, soften or disintegrate when immersed in water [29]. Activated alumina used in adsorption and catalysis are microporous forms of aluminum oxide produced by thermal dehydration of aluminum hydroxides, Al(OH)₃, or hydrated alumina, Al₂O₃(3H₂O). It has a high surface area of 150–500 m²/g with pore sizes ranging between 1.5 and 6 nm and heat of adsorption nearly equals 3000 kJ/kg [30].

Diffusion data in micropore alumina desiccant are essential in order to design and size the appropriate equipment in a range of applications including air dehumidification. Adsorption of water vapor on activated alumina involves several different mechanisms. The experimentally observed equilibrium isotherms represent the

sum of the contributions from chemisorption, quasi chemisorption, physical adsorption and capillary condensation [31]. However, Harding et al. [32] reported that despite all the work conducted over many decades, there remains a major problem in understanding diffusion in alumina. It is certain that all measurements of diffusion in alumina refer to extrinsic diffusion, however, the experimental activation energy is larger than any theoretical prediction by a factor of 2. The authors [32] concluded that a significant body of work is necessary if a satisfactory resolution of the “conundrum of corundum” is to be achieved.

Since each desiccant material has its own properties and micro-pore structure, the diffusion data that control the desiccant performance is a typical characteristic of each material that should be known for cost effective desiccant cooling-systems. Sultan et al. [33] reviewed the various desiccant materials and stated that the work reported for air dehumidification and regeneration processes using activated alumina beds are limited to Refs. [34–36]. Dupont et al. [34] tested silica gel and activated alumina during adsorption and desorption modes and reported that activated alumina requires regeneration temperature less than 80 °C. Such temperature level can be easily obtained using solar collector, heat recovered from industrial processes or from thermal engines [37]. Dupont et al. [34] showed that silica gel transfers about 30% more water vapor per unit dry mass than activated alumina. However, the comparison between activated alumina and silica gel was based on latent capacity and did not include energy efficiency or cycle duration. On the other hand, Abd-Elrahman et al. [35] studied the transient adsorption or desorption characteristics of activated alumina using radial flow desiccant bed composed of hollow cylinder of 90 cm length with outer and inner diameters of 27.8 and 10.8 cm, respectively. Spherical activated alumina particles of 4 mm diameter and 39.86 kg filled the annular space of the hollow cylinder. The experimental tests were carried out at different inlet air temperatures, humidity ratio and regeneration temperature (110–198 °C). Hamad et al. [36] used the same test rig in [35] to simulate the coupled heat and mass transfer in adiabatic desiccant bed. Their results showed that the COP of a desiccant-based air conditioning system is decreasing with time. It should be stated that the use of such thick bed (90 cm) and high regeneration temperatures (110–198 °C) may lower the system COP and cease the advantages of desiccant air dehumidification.

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