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Activated carbon, silica-gel and calcium chloride composite adsorbents for energy efficient solar adsorption cooling and dehumidification systems

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ABSTRACT

Composite adsorbents were synthesized from activated carbon, silica-gel and $CaCl_2$. The optimized condition for adsorption cooling systems was obtained when raw activated carbon was impregnated by soaking in 10 wt.% sodium silicate solution for 48 h and then in 30 wt.% $CaCl_2$ solution for 48 h. A 0.805 kg kg^{-1} of difference in equilibrium water uptake between 25 °C and 115 °C was recorded at atmospheric pressure. Besides, an adsorption rate test unit was built to study the adsorption isotherms and adsorption rates in which 0.23 kg kg^{-1} of adsorption capacity was recorded at 27 °C and a water vapor pressure of 900 Pa. The ideal coefficient of performance (COP) and the average specific cooling power (SCP) for an adsorption cooling system using the composite adsorbent were estimated to be 0.70 and 378 W kg^{-1} respectively. The results demonstrated that the composite adsorbents can be a good candidate for low temperature heat-driven adsorption cooling and dehumidification systems.

Adsorbants composites au gel de silice/chlorure de calcium pour des systèmes de refroidissement et de déshumidification solaires efficaces sur le plan énergétique

Mots clés : Adsorbant ; Charbon actif ; Gel de silice ; Chlorure de calcium ; Système à adsorption ; Déshumidification

1. Introduction

In recent years, global warming and energy shortage have become more and more serious as a trade-off of economic development all over the world. Adsorption cooling systems powered by solar energy or waste heat have drawn increasing attention, as such systems need neither CFCs nor HCFCs as the working fluid and neither fossil fuel nor electricity to drive

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Nomenclature

Symbol	
AC	activated carbon
BET	Brunauer–Emmett–Teller
C_{ac}	specific heat capacity of the activated carbon [J kg^{-1} K^{-1}]
C_{ad}	specific heat capacity of the adsorbate (water vapor) [J kg^{-1} K^{-1}]
COP	ideal coefficient of performance
h_{ad}	heat of adsorption [J kg^{-1}]
h_{fg}	latent heat of vaporization of water [J kg^{-1}]
K	adsorption rate coefficient [s^{-1}]
LDFM	linear driving force model
m	mass of adsorbent at current stage [kg]
m_{dry}	dry mass of the composite adsorbent [kg]
MCM-41	mobile composite material
Q	cooling load [W]
q	equilibrium adsorption capacity [kg kg^{-1}]
$\overline{SCP}$	average specific cooling power [W kg^{-1}]
SCP	specific cooling power [W kg^{-1}]
SEM	scanning electron microscope
T	temperature [K]
t	time [s]
TGA	thermogravimetric analysis
V	volume [cm^3]
X_{eq}	equilibrium water uptake [kg kg^{-1}]
ΔX	the difference between uptake and off-take during adsorption/desorption process [kg kg^{-1}]
XPS	X-ray photoelectron spectroscope

them (Wang et al., 2000; Wang and Wang, 2005; Zhai and Wang, 2009 and Hamamoto et al., 2006). The working principle of an adsorption cooling system is that a large amount of adsorbents packed in an adsorber adsorbs the adsorbate, such as water vapor, from an evacuated container (the evaporator). The water in the evaporator continuously evaporates at low pressure to cool the process air. At the same time, the heat produced due to the adsorption of adsorbent is removed by the cooling water in the adsorber. When the adsorption finishes, the adsorbent is heated by hot water/oil to desorb the water which goes to the condenser and then returns to the evaporator. The thermodynamic cycle for both the adsorption and desorption process is then completed. As an energy efficient solution, the hot water/oil can be heated up by solar energy or waste heat which is free from the environment. The two adsorption/desorption chambers of the adsorption cooling systems work alternatively in order to produce the cooling effect continuously (Saha et al., 2007a,b; Wang et al., 2000 and Zhai and Wang, 2009).

Today, however, traditional vapor compression systems still dominate in almost all applications, since adsorption cooling has disadvantages which need to be improved. The primary disadvantages are: (1) Long adsorption/desorption time; (2) Low coefficient of performance (COP), leading to increased energy consumption and cost; and (3) Low specific cooling power (SCP), leading to a bulky system. To overcome these problems, the adsorbent–adsorbate pair is a core element in the adsorption cooling system design and one direction is to develop new composite materials as effective adsorbents (Li and Wang, 2007). Greater adsorption capacity can give a higher coefficient of performance. Similarly, a higher adsorption rate allows greater specific cooling power. Therefore, enhancing the adsorption properties i.e. adsorption capacity and adsorption rate of the composite adsorbent can definitely increase the value of COP and SCP (Wang et al., 2000).

Many studies (Daou et al., 2007; Restuccia et al., 2004; Wang et al., 2006b and Aristov et al., 2002) have focused on improving the performance of adsorbents by using composite materials. Huang et al. (2010) used silica-gel and activated carbon as a composite adsorbent and reported good adsorption capacity. Daou et al. (2008) used composite adsorbent S40 (microporous silica-gel impregnated in a 40% concentrated aqueous solution of calcium chloride) and reported COP values as high as 0.62 in a single-bed system. Wang et al. (2006a) used $CaCl_2$ and expanded graphite adsorbent for an adsorption ice maker on fishing boats and recorded average SCP of 640 W kg^{-1} Saha et al. (2009) showed that composite adsorbents can improve upon the mass transfer performance of typical chemical adsorbents and can avoid agglomeration. Tokarev et al. (2002) confined $CaCl_2$ in a mesoporous host matrix of a composite material (MCM-41) and improved mass transfer by minimizing agglomeration. Chan et al. (2012) used zeolite 13X/$CaCl_2$ as a composite adsorbent and obtained a difference of 0.404 kg kg^{-1} in equilibrium water uptake (ΔX) between 25 °C and 100 °C at 870 Pa. Gong et al. (2011) presented a novel adsorption chiller using silica-gel/$LiCl_2$ as a composite adsorbent and water as an adsorbate. The COP they recorded from the adsorption chiller system was about 0.43 and the cooling capacity was around 5.3 kW. Indeed, most composite adsorbents could enhance SCP and COP, but the COP and cooling capacity remained quite low. One of the principal reasons for this was the inadequate performance of adsorbents for water vapor adsorption (Wang et al., 2010 and Dieng and Wang, 2001).

This study set out to test a new hydrophilic method of impregnating the micropores of activated carbon with silica-gel and calcium chloride as a way of achieving better water vapor adsorption. Thirteen combinations of these three materials were tested to optimise the adsorption characteristics for adsorption cooling and dehumidification system applications. An adsorption rate test unit was used to study the adsorption capacities and adsorption rates of the various composites, and the ideal COPs and average SCPs for an adsorption cooling system using the silica activated carbon/$CaCl_2$ were also estimated.

2. Experimental methods

2.1. *Conceptual design*

Silica-gel, activated carbon and zeolite 13X are three common adsorbents used in adsorption cooling systems. Each has its