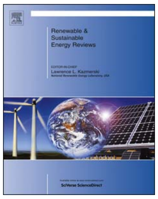
Renewable and Sustainable Energy Reviews 79 (2017) 503–519

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A state of the art of required techniques for employing activated carbon in renewable energy powered adsorption applications

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ARTICLE INFO

Keywords:
Activated carbon
Adsorption cooling
Adsorption kinetics
Isotherms

ABSTRACT

This paper reviews, for the first time, the measurement adsorption characteristics techniques to facilitate optimal testing of the validity of adsorbent materials in adsorption applications. Thermo-physical properties, adsorption characteristics and modelling techniques are presented. The characterisation of material thermo-physical properties includes true and bulk densities, specific heat capacity, surface area, pore volume distribution and thermal conductivity. The adsorption characteristics were categorized into adsorption isotherms and kinetics including experimental and theoretical equations. A range of models used in the simulation of adsorption cooling systems is presented and discussed. The paper highlights the conditions for which each measurement technique is most suitable and the limitations of modelling techniques, which is a vital element in the robust assessment of the performance of adsorption cooling units.

1. Introduction

Worldwide, building air-conditioning systems consume more than 15% of all generated electricity. Such significant electrical energy consumption leads to depletion of fossil fuel resources and production of greenhouse gases. Heat-driven cooling systems utilize waste and/or renewable energy such as automobile exhausts and solar thermal energy to produce a cooling effect with correspondingly lower environmental impact. One such system is sorption cooling which has low global warming potential (GWP) and zero ozone depletion potential (ODP). In recent decades, absorption (liquid/vapour) cooling systems have become commercially available technology, but they still suffer from corrosion, toxicity and crystallisation of the working fluids. Adsorption cooling (solid / vapour) offers several advantages including relatively low electricity consumption (no circulating pump), low driving heat source temperature and high operational reliability due to the low number of moving parts [1–4].

Common adsorbents, which have been studied extensively and employed in adsorption cooling applications, include zeolite, silica gel and activated carbon [5–7]. The activated carbon materials have been used with various refrigerants to produce adsorption cooling systems for low-temperature applications [8–11]. Activated carbon pairs are proposed in this investigation because they have a large surface area and relatively low cost. These adsorbents are manufactured from natural materials and indicate promising performance through chemical modification of their surface characteristics. However, while the advantages of adsorption cooling systems are clear, there remains a number of sub-optimal characteristics such as low performance and relatively high specific volume. Accordingly, much recent research has been targeted towards improving the performance of adsorption cooling systems, including the identification of new adsorption pairs, the improvement of heat transfer coefficient of adsorbents, and the presentation of new applications for adsorption techniques [12–16]. There are accepted stages in the investigation of new adsorbents to determine sufficient data for the validation of performance and suitability in adsorption cooling applications. These steps include i) measuring their physical properties such as density, thermal conductivity and specific heat, ii) establishing their adsorption isotherms, iii) determining their adsorption kinetics, iv) simulating their duty in a modelled adsorption cooling system, and v) evaluating their applica-

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http://dx.doi.org/10.1016/j.rser.2017.05.172
Received 27 September 2016; Received in revised form 3 May 2017; Accepted 20 May 2017
1364-0321/

tion in an experimental adsorption cooling system.

Although the above five steps can be considered a suitably robust testing protocol for any new adsorbent, there is no agreed method for evaluating each of the five stages and therefore numerous different methods have been employed. The aim of the current review was therefore to present these different techniques for determining material thermo-physical properties, adsorption isotherms, adsorption kinetics, and computational modelling techniques with a specific focus on the use of activated carbon.

2. Activated carbon

Activated carbon is a solid material used in granular or powder form, it is black in colour and has the general appearance of charcoal. It is prepared in two stages by, firstly, the carbonization of carbonaceous raw material which is treated in an inert atmosphere at temperatures below 800 °C, and secondly, the activation of the carbonized product [8] as shown in Fig. 1. In the first stage, the cross-linkages between carbon atoms are broken down in the absence of oxygen. At this stage, the adsorbent still has poor adsorbing characteristics as the pores are blocked by carbonization by-products [11]. However, during the activation process, an enhancement of the porosity is triggered by cleaning out of the pores, which occurs through three stages, namely carbonized surface cleaning and exposure to the activating agent, then burning of elementary crystals, and lastly, oxidation with a reduction in the total micro pore volume.

There is a wide range of activated carbon materials reported in the literature, which could be classified according to their (i) physical form, e.g. powders, pellets, or granules; (ii) original carbonaceous source, e.g. olive stones [10], oil palm biomass [11], guava seed-based, and coconut-shell; and (iii) carbon activation methods, e.g. activation by gases or chemicals [6]. Activated carbon has a non-polar or slightly polar structure, which facilitates adsorbing non-polar and slightly polar organic molecules (e.g. ammonia, ethanol and methanol) to a level that is higher than other sorbents. Also, the heat of adsorption, or bond strength, is generally lower in the case of activated carbon compared to other sorbents [6]. Fig. 2 presents the adsorption characteristics of activated carbon materials with ethanol, carbon dioxide, HFC134a and methanol with adsorbent Maxsorb III that has a surface area of 3045 m^2/g (manufactured by Kansai Coke and Chemicals Co. Ltd) . Due to the slow kinetics of Maxsorb III–ethanol pair, it is a candidate adsorbent for solar adsorption cooling where cycle time effect has low importance.

3. Thermo-physical properties

Physical properties of adsorbent materials, such as their particle size distribution, porosity, permeability, density, specific heat capacity, surface area, pore volume distribution and thermal conductivity, have been shown to influence their adsorption uptake and kinetic capacity [6,17]. The ability to measure such properties is therefore necessary for the development of adsorbent materials and their applications as discussed below.

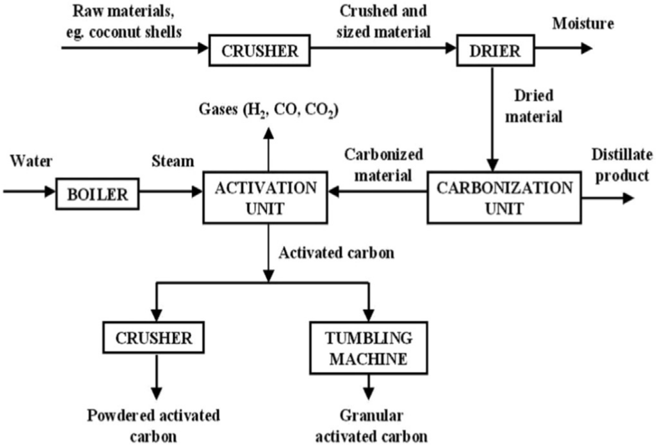

Fig. 1. Flow diagram of activated carbon production [9].

3.1. Particles size distribution and porosity

Powder porosity refers to the voids within the powder bed including spaces between agglomerates, between primary particles, and micro-spaces (micropores) within the particles. Powders with irregular shaped particles and anisometric particles (elongated or flattened shaped particles) have been reported to have more porosity than spherical shaped particles [18]. Powder porosity (ε) is correlated to powder bulk density as (porosity = 1 - (bulk density/true density)) [19].

Particles with low density and high porosity have weaker inter-particle Van der Waals forces. In contrast, powders with increased bulk densities and decreased porosities have higher cohesive forces due to the increase in the number of interparticle contacts. Particle porosity can be measured using mercury intrusion measurements [20]. The principle of this technique is based on the fact that mercury does not wet most substances and hence it will not penetrate pores by capillary action but must be forced into the pores by the application of external pressure. The required equilibrated pressure is inversely proportional to the pore size. Mercury porosimetry analysis is the progressive intrusion of mercury into a porous structure under stringently controlled pressures. The MIP instrument generates volume and size distributions from the pressure versus intrusion data. Mercury porosimeter analysis is recommended for macroporous adsorbents. Gas adsorption is used for mesopores and micropores measurements where nitrogen or carbon dioxide is injected into the pores instead of mercury [21].

Several techniques could be used to determine particle size distribution of adsorbent materials. For example, the sieving method employs several mesh sizes fitted placing the large meshes on top of the smaller mesh sizes. Each mesh holds adsorbent particles above a certain size. Following sieving, the weight of the powder held on top of each sieve size is recorded to get particle size distribution. In general, particle sieving is ideal for particles larger than 75 μm and is not suitable for particles smaller than 38 μm due to particle cohesiveness. Sieving could be performed wet or dry, by hand or by machine. Mechanical sieving is preferable for non-cohesive powders, whereas air-jet sieving is more suitable for cohesive powders [22]. In general, sieving results in particles larger than the sieve holes' diameters, especially for elongated particles.

Other techniques include scanning electron microscopy (SEM) [23], sedimentation methods, opto-electrical sensing, laser diffraction, and photon correlation spectroscopy. In SEM, a focused beam of high-energy electrons interacts with atoms in the sample, generating a variety of signals at the surface of the solid sample. The signals derived from electron-sample interactions reveal much information including the particle size. Qualitative particle size determinations could be obtained by investigating an area having a particular number of particles and measuring the diameter by using the scale bar presented in the images. Sedimentation methods are based on the dispersion of the material particles in a liquid. Particles are allowed to settle and then the particle size is taken as a function of time. In the optical and electrical sensing zone method (Coulter Counter), electrical impedance (resistance) generates a voltage with an amplitude proportional to particle volumes in an electrolyte as they pass through an orifice. Laser diffraction methods use a laser beam that passes through a dispersed particulate sample, and the particle size distribution (ranging from 0.02 μm to 2000 μm) is measured from the angular variation in the intensity of the scattered light. Large particles scatter light at small angles relative to the laser beam and small particles scatter light at