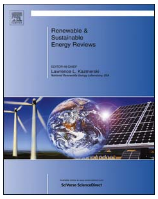
Renewable and Sustainable Energy Reviews 63 (2016) 315–332

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Revisiting adsorption cooling cycle from mathematical modelling to system development

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ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form
29 February 2016
Accepted 13 May 2016

Keywords:
Adsorbent
Adsorption chiller
Heat exchangers
Modelling
System development

ABSTRACT

The urgency to look for promising sustainable alternatives to the conventional vapour compression technique for cooling applications has been strong. As the result, the gas-solid adsorption system has been considered as one of the alternatives to generate cooling effect. This paper reviews the development of this adsorption cooling technique in three different aspects: mathematical modelling, intrinsic, and extrinsic developments, in order to present an overview of this field from basic mathematical representations and designs to current research trends as well as innovative applications and configurations. Various adsorption equilibria, diffusion models, kinetics, and system modelling are reviewed. On the other hand, the roles of both the heat exchanger design parameters and the adsorbent materials are discussed followed by the different bed configurations and schemes. The impact of various operating parameters on the system performance is also covered.

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http://dx.doi.org/10.1016/j.rser.2016.05.059
1364-0321/

1. Introduction

Adsorption can be defined as a process in which the molecules of a liquid or gas contact and adhere to a solid surface. The adsorbent is the substance which the adsorbate is attached on. Chemisorption is an adsorption process which involves chemical reaction between the adsorbate molecules and the adsorbent surface. If no chemical reaction is involved, the adsorption process is then known as physical adsorption or physisorption, in which weak van der Waals forces are formed instead of strong chemical bonds as in chemisorption.

Physisorption requires far less desorption energy compared to chemisorption, which can be 7–8 times lower in the case of ionic bond of electrons sharing against van der Waals bond of CH_2 groups on the same metal surface [1]. Lower desorption energy consumption is favourable in cooling as less heat is used to drive the cooling system. Thus, only physisorption is considered in this review.

The adsorption cooling technique has been gaining attention as a potential alternative to the conventional vapour compression system in an attempt to pursue the goal of preserving the environment and solving the problem of ozone layer depletion. The history of adsorption cooling dates back to 1823 when Faraday [2] discovered the cooling effect from evaporation of ammonia [3]. Since the 20th century, interest in this research topic has been increasing.

The use of various adsorbent–adsorbate pairs in the mentioned cooling technique such as silica gel–water, zeolite–water, and activated carbon–methanol indicates that it is a cooling technique that does not depend on greenhouse gases. For example, HFC (hydrofluorocarbon) in vapour compression cooling system which possesses global warming potential was identified as one of the greenhouse gases under the 1997 Kyoto Protocol [4].

One of the advantages of using adsorption cooling technique is that it can be driven by low grade heat source or waste energy produced by engines such as those in cars and ships. Various adsorption cooling systems driven by exhaust gas of a diesel engine have been designed and tested [5–7]. Solar power can also be used as heat supply to the cooling system. Some of the works can be found in [8–11]. The benefits of a sustainable and environment-friendly cooling system deserve to be studied more extensively in view of its huge potential contribution towards a greener world.

Several reviews have been published on the research findings pertaining to adsorption cooling. Lu and Leong [12] reviewed the possibilities of using adsorption as a replacement for CFC-based cooling systems. Yong and Sumathy [13] reviewed the different types of mathematical models that are used to predict the behaviour and performance of adsorption cooling cycles. The models were classified into three main categories: thermodynamics, lumped parameter, and heat and mass transfer models. Demir et al. [14] compared the performance of adsorption cooling systems of different working pairs and configurations with that of absorption and conventional systems using Coefficient of Performance (COP) as the performance indicator. The advantages and disadvantages of using the adsorption system as well as the problems faced with this technology were discussed.

Srivastava and Eames [15] discussed the various commercial hydrophilic and hydrophobic adsorbents and adsorbent–adsorbate working pair combinations including silica gel–water, zeolite–water, activated carbon–ammonia, and metal hydrides–hydrogen pairs. Aristov [16] reviewed the recent trends in developing more efficient heat exchangers to be used in adsorption systems. Heat exchanger designs were divided into two main categories: loose grains and coated heat exchangers. Details of the effect of different configurations of the heat exchanger design on the system performance were described and reviewed. Li et al. [17] reviewed the development of various types of solid–gas sorption cycles that are driven by low-grade thermal energy. Recently, Sharafian and Bahrami [18] reviewed the various heat exchanger designs that have been developed and their performances. The heat exchangers were categorised into nine groups according to their designs.

The development of adsorption cooling technology has been vigorous throughout the past few decades. To understand the ideas and trends of the tremendous efforts made by various researchers, a comprehensive and integrative review is needed to cover as many areas in this field as possible. In this review, the development of the adsorption cooling technology is split into three main categories: mathematical modelling, intrinsic, and extrinsic development.

2. Mathematical modelling development

2.1. Adsorption equilibrium relations

Practically, the capacity of an adsorbent is impossible to be utilised completely due to mass transfer effects in an actual fluid–solid contacting process. Adsorption equilibrium is the most fundamental property that serves as the base for more practical analyses.

A number of studies have been done to discover the relations between the amount of adsorbed species on adsorbent under certain conditions, such as temperature, pressure, and concentration. The relation between the amount adsorbed and the concentration of this species in fluid or gas phase at a specific temperature is known as an isotherm and the general expression is

$$q = q(C)\text{at constant } T \tag{1}$$

where q is the amount of species adsorbed, C is the concentration of the species in the fluid or gas phase, and T is the temperature during the adsorption.

Likewise, the relation between the concentration and temperature to yield a specific amount of adsorbed species can be expressed as

$$C = C(T)\text{for constant } q \tag{2}$$

Isotherms are widely used to describe the adsorption characteristic since the amount of molecules adsorbed on the adsorbent is more important. Several popular isotherms used for adsorption models are discussed here.

Langmuir [19] assumed that adsorption on an adsorbent surface takes place on an energetically uniform surface without any interaction between the adsorbed molecules. This isotherm is