

An Overview on Mathematical Models of Adsorption Refrigeration System

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Abstract—The present study provides an overview of the various theoretically developed mathematical isothermal models for the analysis of adsorption cooling systems with different adsorption working pairs. After an introduction, the brief history of development of refrigeration systems from the conventional refrigeration system to adsorption refrigeration system, Dühring diagram, and recent progress in adsorption technologies are reported. This work also investigates the applications of the mathematical models for various adsorbent bed stages. The authors predict that the challenges of future research in modification of the mathematical models to approach the industrial application.

Introduction

Energy plays an essential role in the development and progress of a country's economy. The economic growth and technical advancement of developing nations depend on energy which imitates the country's standard of living. In recent decades, an increase in energy demand is observed due to increase in population, energy expenditure per capita and rising economy. Fossil fuels persist to contribute a large amount of energy utilization in the world and oil leftovers the main source of energy. As a result, the global warming occurs when CO₂ released primarily through the combustion of fossil fuels (oil, natural gas, and coal) and other gases, such as hydrochlorofluorocarbon (HCFC), chlorofluorocarbons (CFC), hydro-fluorocarbon (HFC), water vapor, methane, nitrous oxide, and ozone [1]. In addition to global warming and climate change, air conditioning and refrigeration requirements have increased rapidly. Concerning environmental issues, scientists and researchers studied alternative ecological solutions like adsorption cycle. It is the most interesting unconventional technology to save energy and surroundings [2]. Adsorption technology has proven its way in various energy conservative and environmentally friendly applications. Adsorption chillers consume a lesser amount of electrical energy than conventional chillers (VCRS) and can also be operated with lower heat energy sources, such as solar energy or heat loss, requires less maintenance because

of the absence of moving parts such as compressors and working pairs are also eco-friendly [3]. To the best of author's knowledge, approximate no systematic review study is available on various types of the isotherm models for the application of the different working pairs in adsorption cooling system. Therefore, this study provides the various mathematical isothermal adsorption models for various adsorbate adsorbent pairs and their application for specific type of isotherm.

Development of refrigeration systems

In the past few decades, the conventional cooling system (vapor compression cooling system) was developed and utilized for cooling purposes. The vapor compression refrigeration system (VCRS) requires the installation of an expensive mechanical compressor, condenser, expansion valve, and evaporator. VCRS consumes large amount of electrical energy with all its restrictions like accessories, operational and maintenance difficulties, and low capacity. The non-natural, traditional refrigerants like hydrochlorofluorocarbon (HCFC), chlorofluorocarbons (CFC) and the hydro-fluorocarbon (HFC) result in both ozone depletion and/or global warming are used as working fluids. It has a high potential for global warming and ozone layer depletion. These are the main drawbacks of VCRS. To overcome the power consumption (electrical energy) with the use of waste heat energy (solar energy), the vapor absorption refrigeration system (VARs) was developed in 1700s.

Development of adsorption systems

The first proof of the experience of adsorption cooling was found in Faraday's laboratory in 1848. At the present time, global energy consumption and environmental problems are found as two major problems. Therefore, the adsorption cooling technology and heat pump systems are becoming an interesting and upcoming area of research for newcomers by means of successful adaptation of the long duration economic

performance of the adsorption system to lessening the more power consumption problems associated with the environmental pollution.

Adsorption is a process in which a substance penetrates into the pores of crystal blocks, of amorphous solids or of liquids. It occurs due to the interaction between adsorbent (solid) and adsorbate/refrigerant (gas). The adsorption process is a general phenomenon, based on the chemical and physical mode between solid and gas.

The adsorption chilling systems are generally required the lesser heat source temperatures than the absorption chilling systems. The molecules of the adsorbate entrap on the pore's textured surface of adsorbent in two different ways because of different forces involved.

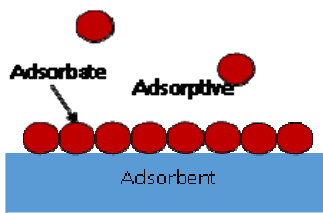


Fig. 1: Adsorption processes

Physisorption or physical adsorption is a category of adsorption process in which the forces involved to attach the adsorbate (refrigerant) molecules on the solid adsorbent surface are intermolecular forces (van der Waals) of the similar type as those accountable for the condensation vapors and the imperfection of real gases, that does not involve a considerable transformation in the electronic orbital patterns of the species concerned.

Chemisorption or chemical adsorption is another way of adsorption process in which the forces involved to fix the adsorbate molecules with the solid adsorbent surface are valence forces of a similar class as those functioning in the creation of chemical compounds. Figure 1 and Figure 2 illustrate the adsorption process and its way respectively.

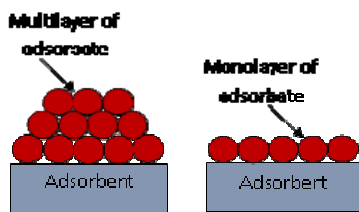


Fig. 2: Physical and Chemical Adsorption [4].

Basic adsorption cooling cycle

The basic adsorption refrigeration cycle consists mainly of four parts (evaporator, thermal compressor, condenser, and expansion valve). Figure 3 shows the simple adsorption cycle.

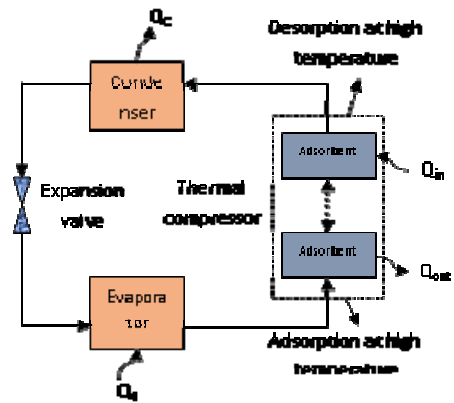


Fig. 3: Vapour adsorption refrigeration system [5].

The ideal adsorption refrigeration cycle is also called the Dühring diagram. It has four processes shown in Figure 4.

Preheating: In this process, the temperature of the adsorbent bed increases due to which the pressure also increases from the evaporation pressure to the condensation pressure.

Desorption: The adsorbent continues to receive heat as it connects to the condenser at constant pressure shown in the Dühring diagram. Vapour desorption takes place because of the temperature increment. This desorbed vapor is liquefied in the condenser.

Precooling: Meanwhile, as the adsorbent releases heat during closure the temperature of the adsorbent decreases. It results in a drop in the pressure of the condensation to evaporation.

Adsorption: In this process, the adsorbent continues to release heat while connected to the evaporator, which now superimposes its pressure. The vapor adsorption takes place due to the continuous decrement in the temperature of the adsorbent. This adsorbed vapor evaporates in the evaporator. Evaporator heat is provided by the low-temperature heat source.

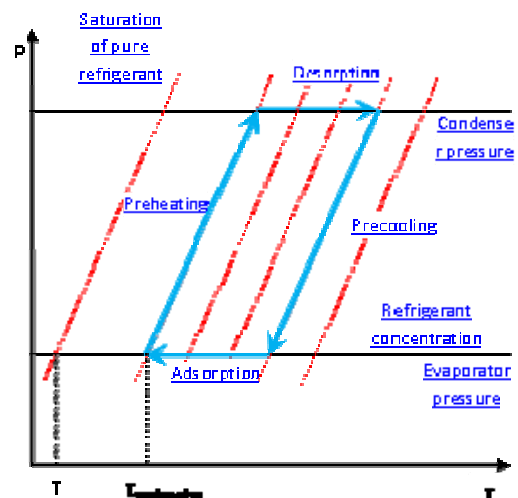


Fig. 4: Dühring diagram [6].

Theoretical models of adsorption cycles

The many researcher-developed mathematical equations to analyze the various adsorbent adsorbate paired adsorption cooling systems (refer Table 1).

Table 1: Various mathematical models for adsorption cooling

Models	Mathematical equations
D-A [used in [7]]	$\frac{W}{W_o} = \exp\left[-\left(\frac{A}{E}\right)^n\right]$ <p>where</p> $A = R_g \ln \frac{P_s}{P}$
Tóth [cited in [8]]	$\frac{x}{x_o} = \frac{\beta P}{[1 + [\beta P]^t]^{1/t}}$ <p>where</p> $\frac{\beta}{\beta_o} = \exp \frac{Q_{sh}}{RT}$
Langmuir [9]	$n(T, P) = \frac{q_m \cdot bP}{1 + bP}$ <p>Where</p> $\frac{b}{b_o} = \exp \frac{\epsilon}{RT}$
Hill [10]	$\frac{W}{W_o} = \frac{\left(\frac{P}{P_s}\right)^{n_H}}{K_D + \left(\frac{P}{P_s}\right)^{n_H}}$
Freund-lich [11]	$\frac{W}{W_o} = \left(\frac{P}{P_s}\right)^{1/n}$
Brunaur, Emmett, Teller (BET) [12]	$\frac{V}{V_m} = \frac{Cx}{(1-x)(1-x+Cx)}$ <p>Where $x = \frac{P}{P_o}$</p>
Modified BET [12]	$\frac{V}{V_m} = \frac{CKx}{(1-Kx)\{1+(C-1)Kx\}}$
Guggenheim, Andersode Boer (GAB) [13]	$\frac{W}{W_m} = \frac{cKa_w}{(1-Ka_w)\{1+(c-1)Ka_w\}}$ <p>Where</p> $c = c_o \exp \left[\frac{\Delta H_1}{RT} \right]$ $K = K_o \exp \left[\frac{\Delta H_2}{RT} \right]$

Sun and Chakraborty Model [14]	$\frac{q}{q_o} = \frac{\beta \left(\frac{P}{\Psi_s}\right)}{\left[1 + (\beta^m - \alpha) \left(\frac{P}{P_s}\right)^m\right]^{\frac{1}{m}}}$ <p>Where $\frac{P}{\Psi_s} = \left(\frac{P}{P_s}\right) \exp \left(\frac{\phi_m}{RT} \left(1 - \left(\frac{P}{P_s}\right) + z\right) \right)$</p> $\alpha = \left(\frac{1}{\exp(z)}\right)^m$
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Summary

Author The present study summarised the various mathematical isothermal adsorption models for various adsorbate adsorbent pairs and their application for specific type of isotherm.

1. For Maxsorb III/ ethanol, RD silica gel/ water, and carbon-based composite/ CO₂ pair at temperature range of 303 K-343 K, the Toth model show better accuracy.
2. The modified BET method results in better for alumina/water, poorly crystalline boehmite/water pair at 295 K.
3. At the temperature range of 288 K to 333 K, the GAB isothermal models fit better for the dried raisins/ moisture working pair.
4. The Sun & Chakraborty model provides better results for AQSOA-Z01/water pair in the range of 298 K-338 K temperature.

Nomenclatures

- n heterogeneity parameter
- b_o equation constant [kPa-1]
- E characteristic energy [J mol-1]
- W, x instantaneous uptake[kg kg-1]
- W_o, x_o maximum uptake [kg kg-1]
- K_D hill constant
- m heterogeneity factor or mass [g]
- Z compressibility factor
- α a coefficient
- β load factor
- A_o, A₁, B, C constants
- V amount of total gas adsorbed
- V_m the monolayer coverage
- H_{fg} enthalpy of evaporation
- ΔH function of the heat of adsorption
- K measure attractive force field of adsorbent
- Q_{st}* isosteric heat of adsorption
- V_m monolayer coverage

a_w	water activity
β	load factor
Φ_m	min. potential energy, kJ/kg
Ψ	surface coverage
z	compressibility factor
P	pressure, Pa
P_s	saturated pressure, Pa

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