Research and Interests

Functional adsorbent materials and environment-friendly working fluids; Innovative system designs; and Utilization of low-temperature waste heat or solar energy

Figure 1. Layout of main research activities vision.

Gas storage

Desalination

Natural Gas Storage

Advanced Adsorption Chillers

Space Cooling

Hydrogen Storage

Micro Cooling

Hybrid Adsorption Cooling

Micro Adsorption Cooling

“Drinkable water from Sea” WO 2006/121414 A1

Technological innovations on low-temperature thermal energy conversion, conservation, storage and potable water production systems
1. Adsorption Sciences and Technology:

1.1 Adsorption Sciences

(i) A theoretical framework for the estimation of the isosteric heat of adsorption between an adsorbate (vapor) and an adsorbent (solid) is proposed based on the thermodynamic requirements of chemical equilibrium, Maxwell relations and the entropy of the adsorbed phase. The derived equation for the isosteric heat of adsorption is verified against three sets of judiciously selected adsorbent + adsorbate data that are found in the literature and the predictions are found to agree within the experimental uncertainties of the reported data.

(ii) A thermodynamic framework for calculating the specific heat capacity \( \left( C_p \right) \) of a single component adsorbent + adsorbate system has been derived and developed using the classical thermodynamics, and these are essential for the design of adsorption processes. The derived formulation of the \( C_p \) is compared with experimentally measured \( C_p \) of adsorbent + adsorbate systems. The purpose of this letter is to fill up the information gap with respect to the state of adsorbed phase to dispel the confusion as to what is the actual state of the adsorbed phase.

(iii) We have developed the complete thermodynamic property fields for a single-component adsorbent + adsorbate system. These equations enable us to compute for the actual specific heat capacity, partial enthalpy and entropy which are essential for the analyses of single-component adsorption processes.

(iv) A considerable progress has been made for the development of novel porous materials with controlled architectures and surface treatment. An important feature of these adsorbent materials is the maximization of adsorption capacity at Henry’s region. A thermodynamic framework is presented to capture the relationship between the pore specific surface areas with the enthalpy of adsorption. Using this approach, the scientific community can be guided to the development of advanced porous adsorbent and adsorbate pairs. The adsorbents with the highest porous surface areas tend to possess lower isosteric heat of adsorption when storing the methane and hydrogen gases at room temperature.

1.1.1 Adsorption isotherms and kinetics

The adsorption characteristics of (i) pure water vapor on two different types of parent silica gels of type “RD” and “A” and Cu sputtered silica gel, (ii) n-butane, methane, R134a and R507A on
functional activated carbon (Maxsorb III), and (iii) ethanol on activated carbon fiber (ACF) of types A-15 and A-20 at temperatures from 273 to 338 K and at different equilibrium pressures are experimentally studied by a volumetric technique and a thermo-gravimetric analyzer (TGA). The thermophysical properties such as skeletal density, BET surface area, pore size, pore volume and the total porosity of silica gel, Maxsorb III are determined.

We have measured experimentally the adsorption kinetics of (i) water on silica gel (type RD, cu-sputtered RD), (ii) ethanol and methanol on pitch-based activated carbon, activated carbon fibers, (iii) ethanol on to surface treated parent activated carbons and (iv) ethanol on Metal Organic Frameworks material namely MIL-101Cr, at different adsorption temperatures ranging from 27 to 70°C, which are suitable for adsorption chiller design. The ligand and metal binding along with mesoporous network of MIL-101Cr are shown if Fig. 2. The mass uptake and uptake rates are measured with cutting edge experimental facilities under a controlled pressure and temperature environment.

Figure 2.(a) Ligand and metal building blocks in the trinuclear \{Cr3(µ3-O)(O2C-)6(F,OH)(H2O)2\} building unit; 2(b) Super-tetrahedra; 2(c) Mesoporous network. Objects in 2(a) to 2(c) are not drawn to scale.
1.2 Adsorption Technologies

1.2.1 Adsorption desalination

“The availability of “fresh water” as a search for quenching global thirst remains a pressing concern throughout the world, although most of Earth’s surface is covered by oceans or saline water. The effort of providing fresh water for the world’s inhabitants seems to be moved in the wrong direction, because, according to the World Health Organization (WHO), at least one billion people do not have access to clean and fresh water, and about 41% of earth’s population live in water-stressed areas, which climbs to 3.5 billion by 2025. So, the demands for new sources and technologies of fresh water are needed. To mitigate these requirements, desalination has been a practical solution”.

Adsorption desalination (AD) is a novel method of producing potable water, despite the adsorption cycle, for cooling applications found in chemical, power and co-generation plants. Hitherto, there are several kinds of commercial-scale desalination plants in many water scarce countries, such as the multistage flash (MSF) type; the multi-effect desalination type; the membrane-based reverse osmosis (RO) plants; the hybrid plants, which combine the RO and MSF processes; and electrodialysis (ED) or electrodialysis reversal (EDR). All of the mentioned desalination methods are found to be either highly energy-intensive to maintain the processes of desalination or prone to serious erosion and fouling problems in the evaporating units operating at elevated evaporating temperatures. The AD cycle is proposed to mitigate the shortcomings of the conventional desalination methods. A layout and process development of advance AD cycle is shown in Fig. 3. The advantages of the advanced AD cycle are that (i) it employs waste heat at low temperatures for the cycle, temperatures of 85 °C or lower; (ii) The vaporization of saline or brackish water in the evaporator is kept at a low temperature, typically between 20–25 °C, to mitigate problems of corrosion and fouling; and (ii) the complete elimination of any bio-contamination by desorption at 65°C or more where any unwanted aerosol-entrained microbes or cells from the evaporator would be killed. In order to attain optimum and cost effective operation of the studied advanced adsorption desalination cycle, extensive studies have been performed on the design and development of self-generative single spool valve, development of low cost concrete silo pre-treatment of brackish or sea water by ozone micro-bubble, thermophysical properties of carbon nano tubes and other related sub topics. Most of the research work related to adsorption desalination has been conducted in collaboration with many renowned Japanese and overseas colleagues.
1.2.2 Advanced Macro Adsorption Cooling Systems

(i) Multi-stage cycles

The breath of my research interest lies mainly within the field of air conditioning and...
refrigeration, which involves the design, optimization, construction and demonstration of several innovative thermally driven adsorption (solid/vapor) systems, namely, two–stage adsorption chiller, three–stage adsorption chiller and conventional multi–bed adsorption chiller. These chillers can re–utilize low temperature waste heat for useful cooling applications thereby reducing in environmental pollution (thermal as well as gaseous emissions) as lower fossil fuels inputs are required at the power station. All three innovative systems use silica gel–water as the adsorbent–refrigerant pair. This pair is well suited to low–temperature heat utilization and is environmentally benign. The first two chillers can exploit waste heat around 50ºC in combination with a coolant at 30ºC. No other system can produce cooling energy with this extremely low driving source temperature. A photograph of the silica gel-water based three-stage chiller is shown in Fig. 4. This chiller can deliver cooling energy at heat source temperature as low as 40ºC.

Based on the practical knowledge of single and multi–stage adsorption chiller operations, a thermodynamic formulation to calculate the minimum driving heat source temperature of an advanced solid sorption cooling device, and it is validated with experimental data. This formalism has been developed from the rigor of the Boltzmann distribution function and the condensation approximation of adsorptive molecules. The derived minimum driving heat
source is plotted against the number of stages, n in Fig. 5. Experimental data from single-, two-, and three-stage adsorption chillers are also shown therein. In principle, a ten-stage chiller can be driven with a heat source only 2.2°C above the ambient. It is observed that a heat source at as low as 45°C is enough to drive a three-stage adsorption chiller for producing refrigeration at 7 °C, with condensation at 30 °C.

Figure 5. Minimum heat source temperatures versus the number of stage (s) of adsorption cooling cycle.

(ii) Dual-mode, multi-stage non-regenerative, multi-bed regenerative cycle
The main disadvantages of staged regeneration adsorption chillers are their high initial costs and poor performance in terms of chillers coefficient of performance (COP). In order to achieve better performances in adsorption cooling systems, Professor F. Meunier of the CNAM–IFFI of France introduced cascaded adsorption systems. However, Meunier did not focus on low–temperature driven chillers. The system based on Saha et al. (1997) is a low–temperature driven regenerative single–stage, multi–bed chiller. The novel chiller design demonstrates the high efficiency of heat recovery from the heat sources using the serially–connected and multi–bed approach. In another endeavor, we have designed and constructed a dual-mode, multi-bed regenerative and multi-stage non-regenerative chiller and the photograph of the dual-mode chiller is shown in Fig. 5.
(b) Electro-adsorption chiller for micro cooling

This invention describes the successful amalgamation of the thermoelectric and the adsorption cycles into a combined electro-adsorption chiller (EAC). The symbiotic union produces an efficiency or COP more than two folds when compared with their individual cycles. Experiments conducted on the bench-scale prototype show that it can meet high cooling loads, typically 120 W with an evaporator foot print of 25 cm² maintaining evaporator surface temperature of 22°C. A new pool boiling correlation has been developed for water boiling in a cu-foam cladded evaporator where its system pressure is about 1.8 kPa. The COPs of EAC chiller varies from 0.7 to 0.8 which is comparable to the theoretical maximum of about 1.1 at the same operating conditions. With a copper-foam cladded evaporator, the high cooling rates have been achieved with a low temperature difference.

1.2.3 Energy storage systems

Clean energy has played only a small part in today’s energy picture, but it will contribute significantly in the future. The future of energy systems appears to be dominated by new and emerging technologies such as hydrogen-based technologies, advanced adsorption systems,
new photo-voltaic materials, etc. However, hydrogen may require pressurizing the gas which is the simplest approach to hydrogen fuel storage.

Natural gas (NG) is a potentially attractive fuel for automobiles as NG vehicles are environmentally friendly, emitting less carbon dioxide and several other air pollutants. The conventional techniques of using a compressed natural gas (CNG) source (mainly methane) are problematic as high pressures are required. So there is great motivation to develop more efficient low-pressure gas storage systems.

An alternative but promising method of storing hydrogen is to employ the adsorption know-how where the adsorbed system utilizes the vapor uptake properties of adsorbent but at a much lower gas pressures. Adsorbate, such as methane or hydrogen, could be stored at lower pressures but sacrificing marginally on the storage capacity. Highly porous activated carbons are used as adsorbent and the adsorbed phase lowers the pressure in the storage vessel and thus providing higher safety. In the adsorbed form, the quantity of methane storage is comparable to most commercial systems employed to date.

The release of adsorbed NG (mainly methane) is performed by a simple depressurization process or the heating of the container where the required amount of heat is obtained from the exhaust flue gas of the fuel cell where the methane is burnt (found in automobiles). The economic advantages of the proposed Adsorbed natural gas (ANG) storage system sorption are as follows:

(i) Firstly, as the adsorbed phase of NG is stored at a relatively low pressure (typically below 30-40 bars), the wall thicknesses of storage cylinders could be made much thinner than those of CNG (pressure 350 bars). Thus, the low NG pressures ensure greater safety for small storage vessels and the NG could be transported in vehicles to remote regions or for domestic applications.
(ii) A slow gas release rate and a simpler controller are required and the chance of accident is lower.
(iii) Adsorption uptake efficiency is high and system is scaleable for capacity upgrade.
(iv) Ease of transport.
(v) Low temperature for regeneration, even at room temperature.
(vi) Adsorbent lasts several thousand times of re-use.

The following research directions could be conducted in future;
To build-up facilities for measuring the adsorption characteristics and isotherms of promising and new adsorbents such as the activated carbon, activated carbon fibers, MOFs, etc. and these data are useful for hydrogen and methane storage systems. These experiments are essential in determining the energetic performance of hydrogen and methane based adsorption storage.
From such experiments, a new and fundamental design, on storage systems would emerge and they could compliment the system modeling studies as well.

*Potential applications*

(i) The application of natural gas storage employing adsorption phenomena is more attractive. Being charged at low cylinder pressure (less than 30 bars), the distribution of natural gas to domestic consumers and other users in remote regions is much safer as compared to compressed natural gas cylinders where the system pressures tend to be as high as 300 bars which could pose a severe safety problem.

(ii) Its potential applications in automobiles as main energy sources in future when methane acts as the fuel source.