International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.2, pg : 103-111 1 Feb. 2013

Comprehensive Review on Adsorption Heat and Mass Exchange

Shraddha Gondane, **R. S. Shelke**

Department of Mechanical Engineering Department,
G.H. Raisoni College of Engineering , Nagpur-440016, India
shraddhagondane@gmail.com, Shelkerupesh@yahoo.com,

Abstract

The increase in energy consumption in world leads to serious environmental problems, especially global warming and resource depletion. So, in order to reduce such problems use of renewable energies, energy recovery and energy conservation are inevitable. At present, there are large quantities of low-temperature energy released to the environment such as industrial waste heat and solar energy. This can be utilized by transforming them to high-temperature energy. The process of adsorption is a reversible process by which a gas or liquid molecules are fixed onto a solid matrix, typically a surface or a porous material. When the molecules get stick to the voids, they lose some energy, so adsorption is exothermic. The reverse process is called desorption and it is endothermic. The concept of adsorption heat and mass exchange is used in thermochemical heat pump and chillers. This article presents the critical review of work carried out by research scholars in this upcoming area.

Keywords: Depletion; Adsorption; porous material; Desorption; thermochemical; chillers.

Introduction

The adsorption (solid vapor) cycles have distinct advantage over the other heat driven refrigeration cycle, in their ability to be driven by heat of relatively low, near environmental temperature. Under the cycle, waste heat below 100℃ can be recovered. Many adsorbent/adsorbate pairs have been used in adsorption refrigeration/heat pumping system. Silica gel water adsorption chiller is regarded as a candidate technology to utilize low temperature heat of 70~80 ℃. In the Development of Waste Heat Driven Multi-Bed, Multi-Stage Regenerative Adsorption Chiller, the importance of heat recovery system is very crucial. Combined power plant can be benefitted by this method.

The steam from last stage of turbine is trapped in the bed. Later, this enthalpy can be used to upgrade the heat or as cooling in refrigeration industry using thermochemical heat pump. The adsorption process involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The adsorbing phase is the adsorbent, and the material concentrated or adsorbed at the surface of that phase is the adsorbate. Physical adsorption is caused mainly by van der Waals forces and electrostatic force between adsorbate molecules and the atoms which compose the adsorbent surface, figure 1. Thus shows adsorbents are characterized first by surface properties such as surface area and polarity. A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume inevitably gives rise to large numbers of small sized pores between adsorption surfaces. The size of the micropores determines the accessibility of adsorbate molecules to the internal adsorption surface, so the pore size distribution of micropores is another important property for characterizing adsorptivity of adsorbents. Especially materials such as zeolite and carbon molecular sieves can be specifically engineered with precise pore size distributions and hence tuned for a particular separation.

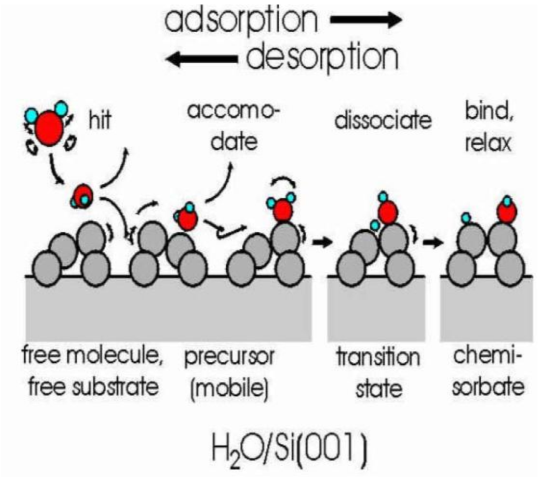


Fig.1 Mechanism of adsorption and desorption

Literature review

Takao Kashiwagi et al, [1] A multi-bed multi-stage adsorption chiller is proposed and studied. The chiller is automatically switching between conventional and multi-stage modes, and thus optimized for alternating temperatures of various heat sources. An experimental prototype of proposed chiller is built to investigate the performance of the chiller and to determine the driving heat source temperature levels of various modes of the chiller. The simulation codes of different modes are also developed to investigate the design and operating conditions of chiller. It is seen that the two-stage and three stage mode of the chiller could run with very low heat source temperature (40~60°C). Though the COP (Coefficient of performance) of three-stage and two-stage mode is quite low, however, the system is effective to utilize low grade waste/renewable heat source, which finally contributes to mitigation of global warming. An advanced single stage called mass recovery cycle is also studied. It is proved that the single stage cycle with mass recovery process improve the cooling capacity of the chiller. The performance of adsorption chiller mainly depends on the heat and mass transfer characteristics of the adsorbent materials. The study also investigates the heat and mass transfer characteristics of adsorbent materials such as, silica gel and carbon fiber. Though the COP is low, the multi-stage chiller produces cooling effectively even the temperature of the source is low, such as,

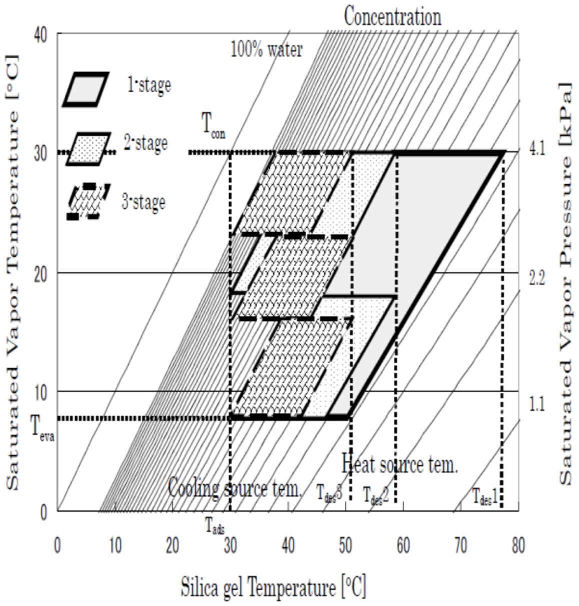


Fig. 2 Conceptual P-T-X diagram for conventional and multi-stage adsorption cycles

From figure 2 one can see that the conventional cycle is not operational with 50°C heat source temperature if the cooling source temperature is 30°C or more. In order to enable the practical utilization of these temperatures to adsorption chiller, multi-stage regenerative strategy can be applied. As can be seen from the figure 2, the adsorption allows the regenerating temperature lift *(T_{des}-T_{ads})* to be reduced by splitting the refrigerant saturated vapor temperature (or pressure) lift between evaporator and condenser *(T_{con}-T_{eva})*. Mass recovery process with heating and cooling in single-stage mode improves specific cooling power (SCP) values significantly and the process is more effective for relatively low heat source temperature, especially at heat source temperature below 60°C

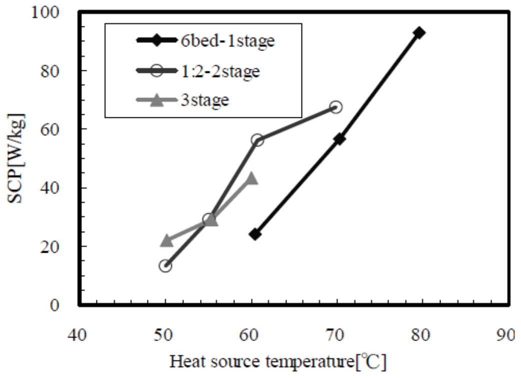


Fig. 3 Effect of heat source temperature

From the Figure 3, it can be seen that three-stage chiller provides better SCP values if the heat source temperature is below 55 °C, single-stage mode provides better SCP value if the heat source temperature is relatively high (>75 °C).

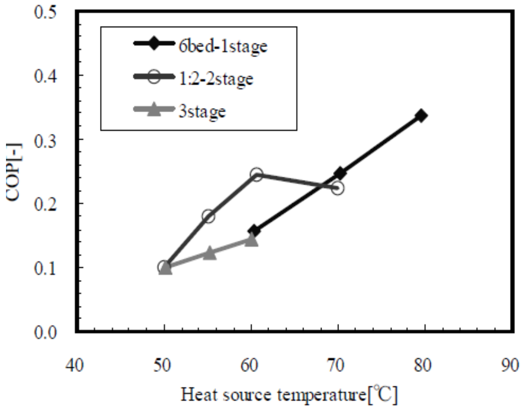


Fig. 4 Effect of heat source temperature

It can be observed from fig. 4 that single stage mode provides better COP value comparing with single and three-stage modes if the heat source temperature is between 50 and 69 °C, while single stage mode provides better COP if the heat source temperature is greater than 69 °C.

Professor G. Wall, [2] This paper describes the application of a thermochemical heat pump for upgrading industrial waste heat. A heat pump with a temperature lift of 50-100ºC is necessary in order to upgrade industrial waste heat. A thermochemical heat pump is theoretically able to do this.

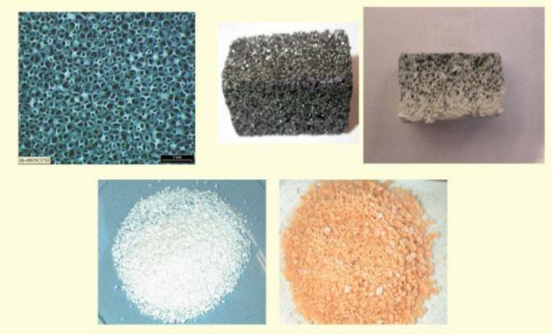


Fig. 4 some adsorbent materials

There are two applications in this field. Process specific upgrading of waste heat across the pinch temperature. The system operates at three temperature levels for both applications. These temperature levels are the waste heat temperature, the ambient temperature and the temperature of the upgraded heat. The system consists of two reactors, each containing a different salt. For this specific system use is made of lithium chloride as low temperature salt (LTS) and magnesium chloride as the high temperature salt (HTS). Ammonia vapor is exchanged between these two salts. Industrial waste heat is used to free the ammonia from the LTS. The ammonia flows, driven by the pressure difference between the two reactors, to the HTS and reacts with the HTS. This exothermic reaction delivers heat at high temperature. During the regeneration step the ambient temperature cools the LTS and the waste heat heats the HTS. The ammonia vapor flows back to the LTS under these conditions. Both the LTS and HTS reactor vessel are built in two fold in order to achieve a continuous system. A switching control system determines whether the above pair of reactor vessel are loading (regenerating) or discharging. The other vessels are running in the reverse process.

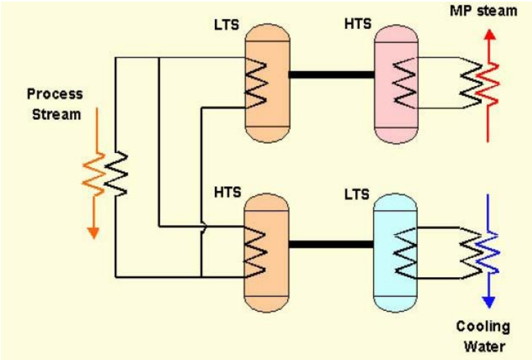


Fig. 5 upgrading industrial waste heat with a thermochemical heat pump

K.C.A. Alam et al, [3] This article presents a numerical investigation of the heat exchanger design effect on the performance of closed cycle, two-bed adsorption cooling systems with silica gel as adsorbent and water as refrigerant. It is well known that the shorter the cycle time, lower is the performance (cooling capacity and coefficient of performance). A long cycle time is responsible for lower cooling capacity. In this study, a non-dimensional switching frequency, which is inversely proportional to the cycle time, is defined and an optimum switching frequency is derived based on parametric analysis. The effect of other heat exchanger design parameters such as adsorbent number of transfer unit (NTU), bed Biot number (Bi), the heat exchanger aspect ratio (Ar) and the ratio of fluid channel radius to the adsorbent thickness (Hr), on the system performance has been investigated. A schematic of an adsorbent heat exchanger is shown in Fig.6a Side view of the main portion of the adsorbent heat exchanger is traced in Fig. 6b. The adsorbent heat exchanger is divided into two parts. One is the adsorbent side, which is called with the adsorbent particles and the other is the heat transfer fluid side as illustrated in Fig. 6c. The role of the heat transfer fluid is either to cool down or to heat up the adsorbent particles, which causes the heat exchanger to adsorb refrigerant vapor from the evaporator or to desorb the refrigerant to the condenser. The system performance is very much sensitive to the switching frequency; ω there is an optimum ω for a given set of design parameters. The optimum ω for the present base run case is estimated as 0.27 for COP requirement and 0.43 for non-dimensional specific cooling capacity (NSCC) requirement. It is seen that the COP and NSCC may not be optimized at a same switching frequency. The optimum o for COP requirement is lower than that for NSCC requirement. Optimum ωo as well as system performance increases with the increase of NTU and Hr, but decreases with the increase of Bi and Ar. It may be concluded that the cycle time of an adsorption refrigeration system is strongly dependent on the configuration of the heat exchanger. The system performance will be lower if the cycle time of the system is set far from the optimum cycle time.

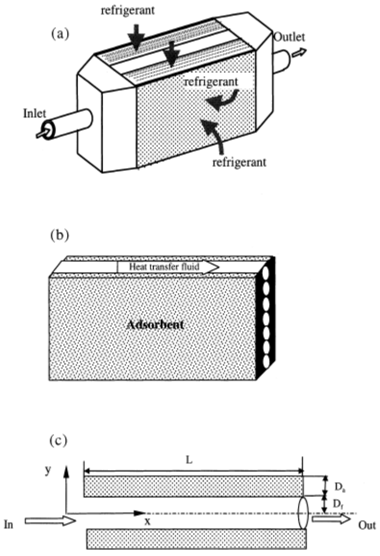


Fig. 6a. Schematic of an adsorbent bed heat exchanger.
6b. Schematic of side view of the adsorbent bed heat exchanger.
6c. Schematic of a flow channel.

A. Rezk et al,[4] This paper theoretically investigates the effects of various adsorbent bed heat transfer enhancement techniques on the adsorption system cooling capacity and some of the methodologies used to enhance the heat transfer performance of the adsorbent in terms of improving the bed thermal performance and the overall cooling capacity of the adsorption system. Firstly, coating the first adsorbent layer to the metal surface and packing the rest of adsorbent granules to eliminate the thermal contact resistance between heat exchanger metal and granules while keeping the same level of permeability. Secondly, adding various metal additives to the adsorbent in order to enhance its thermal conductivity. Finally, the combined effect of using both techniques simultaneously was investigated. All these investigations were carried out using fixed bed dimensions but at various fin spacing. Results showed that eliminating the contact resistance by sticking the first layer of adsorbent granules and packing the remaining ones averagely improves chillers cooling capacity and COP by 8.9% to 4.6% respectively.

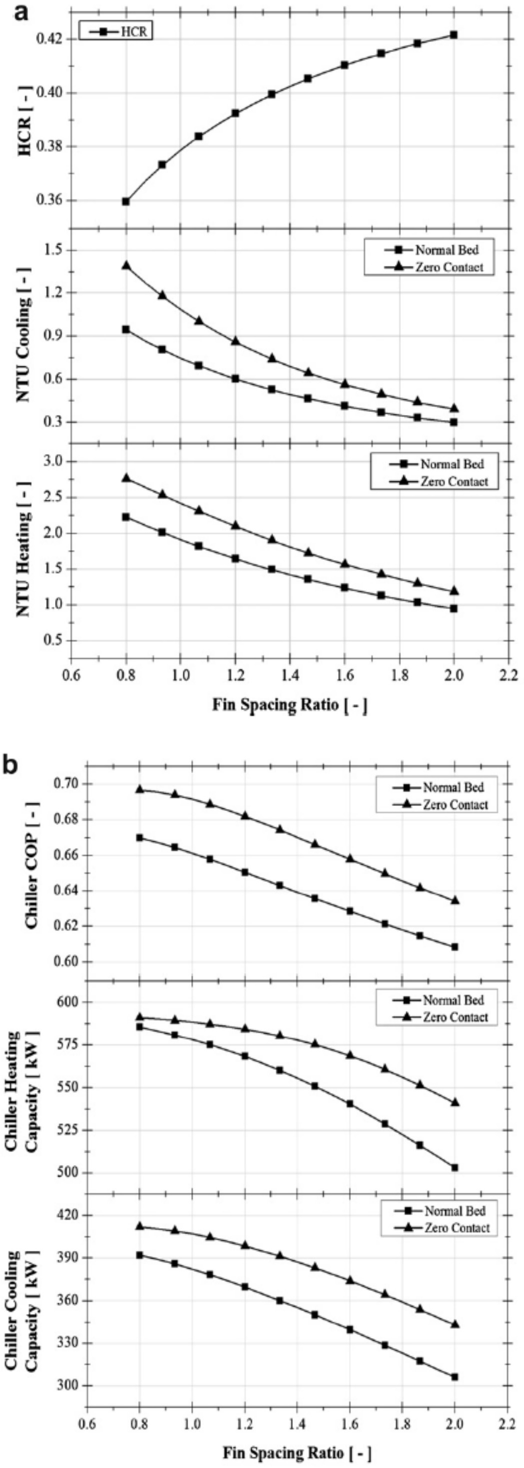


Fig. 7 Effects of eliminating contact resistance on adsorbent-bed thermal performance a. and chiller overall performance b. at various fin spacing ratio

Using different metal additives improves the heat transfer performance of adsorbent bed, up to 58.2% increase in the adsorbent-bed NTU during cooling with Aluminum additives which leads to 12.5% enhancement in the chiller cooling capacity at fin spacing ratio of 2.

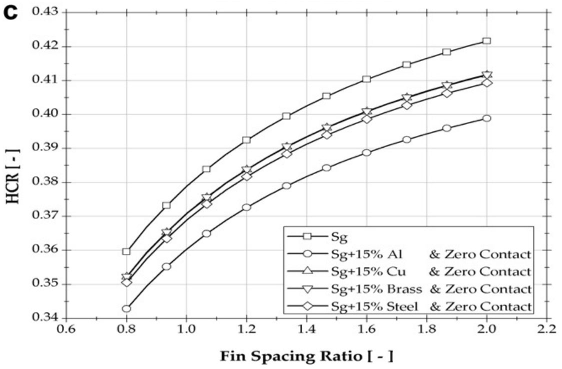


Fig. 8 The effect of metal additives on adsorbent-bed thermal performance.

However, at lower fin spacing ratio (FSR<1.2), a negative enhancement was experienced which can be attributed to the increase in the ratio of metal to silica gel mass. Results for the combined techniques showed that the enhancement in the cooling capacity increases with the increase in the fin Spacing ratio to be maximum of 25% at FSR equals 2. Similar trend has been noticed for the COP where it reached a maximum of 10%.

C.Y. Tso et al,[5] This study aims at improving the performance of a waste heat driven adsorption chiller by applying a novel composite adsorbent which is synthesized from activated carbon impregnated by soaking in sodium silicate solution and then in calcium chloride solution. Modeling is performed to analyze the influence of the hot water inlet temperature, cooling water inlet temperature, chilled water inlet temperatures, and adsorption/desorption cycle time on the specific cooling power (SCP) and coefficient of performance (COP) of the chiller system with the composite adsorbent. The simulation calculation indicates a COP value of 0.65 with a driving source temperature of 85 ℃ in combination with coolant inlet and chilled water inlet temperature of 30 ℃ and 14℃, respectively. The most optimum adsorption desorption. Cycle time is approximately 360 s based on the performance from COP and SCP. The delivered chilled water temperature is about 9℃ under these operating conditions, achieving a SCP of 380 W/kg. The performance of a silica activated carbon/CaCl2 and water based adsorption chiller is modeled. It is found that the performance of the adsorption chiller incorporating the composite adsorbent, in terms of coefficient of performance (COP), specific cooling power (SCP) and chilled water outlet temperature are better than those of the commercially available silica-gel and water based or activated carbon and water based adsorption chillers and even better than some improved adsorption chillers.

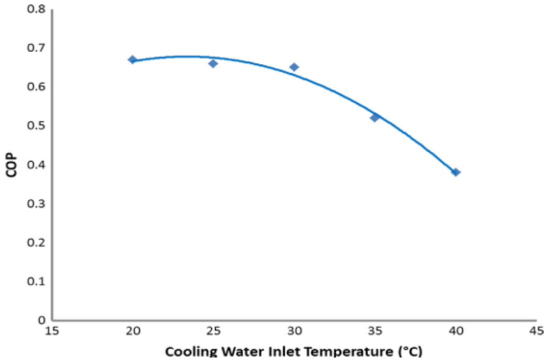


Fig. 9 Effect of cooling water inlet temperature on COP.

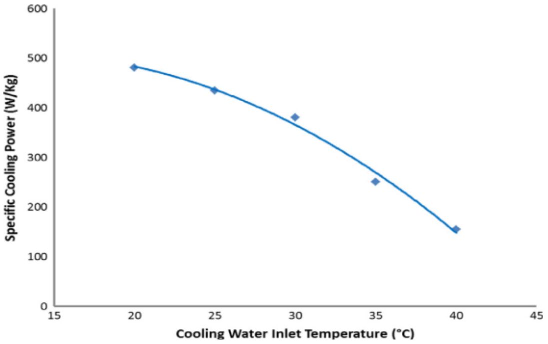


Fig. 10 Effect of cooling water inlet temperature on SCP.

The simulation results also show that high SCP and COP of the adsorption chiller can be obtained (380 W/kg and 0.65, respectively), when the hot water temperature is 85℃, cooling water inlet temperature is 30 ℃ and chilled water inlet temperature is 14 ℃. The heat source temperature is well suited to waste heat and room temperature water can be utilized in the cooling water tank.

Jin Sun et al, [6] This study provides a fundamental view of heat and mass transfer process within the granular particle pores. An initially dry granular silica gel bed is subject to a sudden uniform air flow at a selected temperature and humidity. The coupled non-equilibrium heat transfer and moisture transfer were investigated experimentally and numerically. It was found that only a small fraction of internal surface area of silica gel is exposed to water vapor during the test and this occurs very slowly with a time delay that must be accounted for in the model. This modified model gives transient response results that agree with the experimental data within the uncertainty bounds. In this paper, a transient, non-linear, one-dimensional numerical model was presented to investigate the coupled moisture transfer and non-equilibrium heat transfer when humid air flowed through a bed of initially dry silica gel particles. Compared to the open literature, further improvement of the authors' model was made by attaching much importance on the specific surface area in the calculation of water adsorption rate by assuming it was exponentially time-dependent. This assumption is verified by good agreement between the simulation results and experimental data tested at different inlet air relative humidity conditions for two silica gel particle sizes.

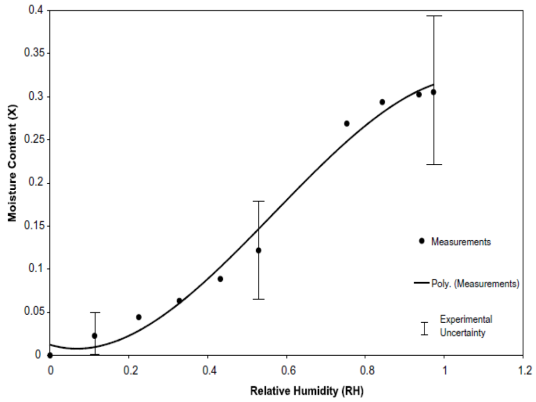


Fig. 11 Equilibrium moisture content as a function of relative humidity at room temperature (295.15K) for silica gel particles (dp ≅1 mm).

The size of the silica gel particles is important for the transient response of temperature and humidity. For the same test condition and the same volume of the particle bed, smaller sized particles with larger total specific surface area adsorb more moisture and therefore release more heat than bigger particles.

K. C. Ng et al, [7] In designing adsorption chillers that employs silica gel-water as adsorbent- adsorbate, the objective is to utilize the low temperature waste heat sources from the industry. This paper describes an experimental approach for the determination of thermodynamic characteristics of silica gel-water working pair that is essential of for the sizing adsorption chillers. The experiment incorporated a moisture balance technique, a control volume variable pressure apparatus (CVVP) and three types of silica gel have been investigated, namely the Fuji Davison type A, type 3A and type RD. As evidenced by experimental results, a Henry type equation is found to be suitable for describing the isotherm characteristics of silica gel-water working pair at the conditions of adsorption chiller. The regeneration of adsorbent depends on the correct allocation of temperature as well as the amount of regeneration time. From the experiments, the isotherm characteristics of silica gel-water in low to high pressure regimes and hence, its isosteric heat of adsorption will be determined. Key parameters for optimizing the amount of heat recovery such as the cycle and the switching time of chiller can also be implied from the measured result.

Li Yong, K. Sumathy, **[8]** According to the paper, a multi-bed adsorption rotary cooling system can make use of the concept of heat regeneration cycle and recently developed technology of heat enhancement in adsorbent bed. In the present study, the performance parameters such as COP and specific cooling power (SCP) of the rotary system are initially analyzed based on heat recovery temperature difference and counter-flow heat exchanger, and meaningful parameters related to the heat transfer fluid (HTF) and the system design are identified. Then, an integrated thermodynamic and heat transfer model of the system is developed and used to evaluate the effect of important design and operational parameters. Results show that the performance of system with certain adsorbent/ adsorbate pair is sensitive to Reynolds and Prandtl number of heat transfer fluid. Also, the module number and module heat transfer area play an important role in improving the system COP and SCP. This study shows that, the performance of the system could be improved further by optimizing the cycle time.

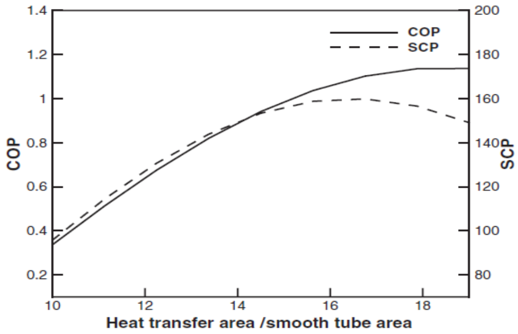
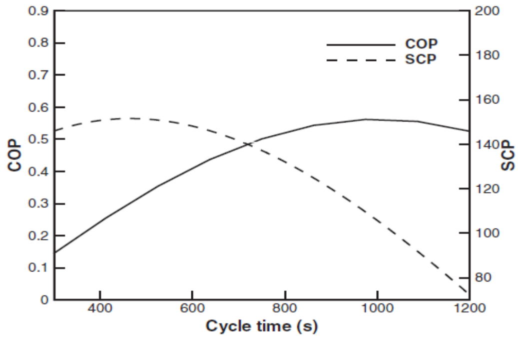


Fig. 12 COP and SCP vs. module heat transfer area

.



.

Fig.13 Effect of cycle time on the system performance.

A heat transfer fluid with low Pr number is recommended for multi-bed adsorption rotary cooling system so that the system could act as a counter-flow heat exchanger. The fins effect is significant in certain range, however, when the effective fin area increases beyond 16 times of the smooth tube area; the fin has a negative effect on SCP (specific cooling capacity).

Mitsuhiro Kubota et al, [9] Silica gel/water type adsorption heat pump (AHP) is considered to be a promising low-temperature heat utilization system because of its ability to utilize waste heat below 353 K and to generate cooling energy for air conditioning. However, the widespread realization of AHP system has not yet been achieved due to its large footprint, which results from the low power density of the AHP system. In order to improve cooling output performance of the AHP by enhancing heat and mass transfer rates of the adsorber, a fin-type silica gel tube (FST) module consisting of circular finned-tube heat exchanger with silica gel packed between the fins was developed in previous work. Further, based on the numerical analysis, the optimal fin pitch and fin length of the module were proposed. In this study, a prototype AHP with the new adsorber consisting of the optimized FST modules was made and cooling output performance of this prototype AHP was investigated under various operating conditions. As a result, the ability of the AHP to continuously generate cooling energy, by utilizing a heat source of around 333–353 K, was confirmed. Further, cooling output and COP were found to increase with an increase in hot water inlet temperature. Finally, it was experimentally verified that the optimized FST module can achieve more than twice higher cooling output per unit adsorber volume than the un-optimized module.

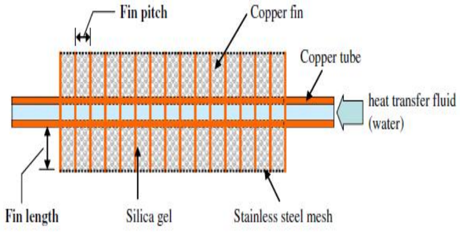


Fig. 14 Schematic drawing of the fin-type silica gel tube (FST) module

T.S. Ge et al, [10] A one-rotor two-stage rotary desiccant cooling system (OTSDC), in which two-stage dehumidification process is realized by one desiccant wheel, was investigated experimentally. The system was proposed to reduce the volume of two stage rotary desiccant cooling system (TSDC) with desiccant wheels without reduction in system performance by using the novel configuration. An experimental set up was designed and built to evaluate the system performance under various operation conditions. The effects of different wheel thicknesses at various rotation speeds under Air-conditioning and Refrigeration Institute(ARI) summer and humid conditions were investigated .It is observed that there exits an optimal rotation speed where moisture removal of the system D and thermal coefficient of performance COP_{th} are both optimal. Moreover, the unit with wheel thickness of 100mm performs better for its bigger moisture removal D and higher COP_{th}. Generally speaking, the COP_{th} of this unit is around 1.0 when their generation temperature is lower than 80℃. Compared to TSDC, the OTSDC not only preserves the merit so flow regeneration temperature and high COP, but also has a reduced size by about half.

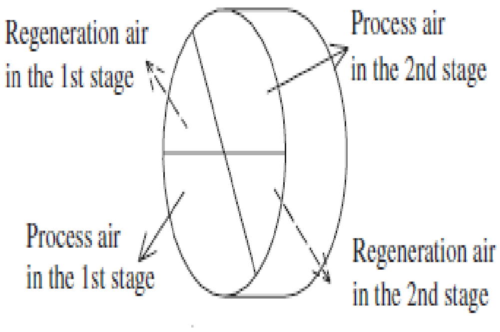


Fig. 15 Rotary exchanger

A. Kodama et al, [11] An effective prediction is proposed to estimate the optimal rotational speed and performance of rotary adsorber, in which simultaneous enthalpy and humidity changes are dealt with separated by visualizing changes of state of product or exhaust air on psychometric chart. assuming that adsorbent rotor is completely regenerated to equilibrium with regeneration air during the corresponding period, the optimal rotational speed corresponds to the region of short time adsorption in which penetration theory holds and enthalpy exchange between both streams through the adsorbent rotor follows the behavior of the rotary sensible heat exchanger at lower resolution rates The change of product/ exhaust air condition with increasing rotational speed is presented as result of simple questions. Also, by considering the relative humidity of product air and that of regeneration air to be almost the same at sufficiently high flow rates of regeneration air, an optimal rotation speed and the product air conditions are easily found by simple calculation. In comparison with experiments the proposed method gives a rotational speed near the optimum and humidity and temperature of the product air are predicted most exactly.

J. Llobet, V. Goetz [12] The rotary process presented here is designed for continuous operation and to use the concept of a heat regeneration cycle developed for solid sorption cold production systems. Based on the analysis of the thermodynamic cycle followed by the reagent, the system is modeled in the form of counter flow heat exchangers in series. This allows an estimate of the energy performance of the process in terms of coefficient of performance (COP) and cold production capacity. It appears that for a given set of thermodynamic operating conditions, the number of transfer units (NTU) of the heat exchangers is the parameter, which conditions the value of the COP. A comparison between the rotary system by adsorption and by chemical reaction helps to select the ideal reagent according to the temperature level for cold production.

Pascal Stabat, Dominique Marchio [13] A desiccant wheel model has been developed in the aim to be adapted to building simulation tools. This model fulfils several criteria such as simplicity of parameterization, accuracy, possibility to characterize the equipment under all operation conditions and low computation time. The method of characteristics has been applied to the heat and mass transfer partial differential equations. This transformation provides new equations which are similar to those of a rotary heat exchanger. Then, the model is described by the Effectiveness-NTU method and it is identified from only one nominal rating point. The model has been compared to experimental and manufacturers' data for a broad range of operating conditions. A good agreement has been found.

X.J. Zhang et al, [14] A one-dimensional coupled heat and mass transfer model, which is expected for use in designing and manufacturing of a honeycombed rotary desiccant wheel, is presented in this paper. The mathematical model has been validated using a real desiccant wheel, and the calculation results are in reasonable agreement with the experimental data. Based on this model, the temperature and humidity profiles in the wheel during both the dehumidification and the regeneration processes are analyzed and verified by experimental data. The numerical results indicate that in the regeneration process a hump curve of air humidity ratio along the channel exists all the time. In the regeneration process the hump of air humidity ratio moves from the duct entrance to the duct exit and increases gradually until the hump reaches the duct exit, where the hump will drop subsequently. The effects of velocity of regeneration air $V_{reg,}$ inlet temperature of regeneration air Tr_{eg} and velocity of process air V_{ad} on the hump moving speed are investigated. To improve the performance of desiccant wheel, it is essential to accelerate the hump moving from the duct entrance to the duct exit as soon as possible.

Ruud J.H. et al [15] This paper describes the experimental performance of two bed silica gel/ water adsorption chiller. A simple model was developed to aid the design and predict the performances. The system comprised two identical sorption reactors operating out of phase in order to ensure continuous cold production. One sorption reactor consisted of six commercially available automotive plate/fin heat exchangers in which silica gel grains were accommodated between the fins. The system was tested as to the power delivered at 12 °C and the power density. The average cooling power was 3.6 kW. This is only 72% of the design value and can be largely attributed to the lower heat transfer fluid flow rate through the sorbent reactor. The thermal efficiency, COP, was 0.62 and the power density was 17 kW/m^3 for the system as a whole.

Fig. 16 Design drawing of the reactor assembly consisting of six heat exchanger units.

Takahiko Miyazaki, Atsushi Akisawa, [16] The research investigated the influences of heat exchanger parameters, such as heat capacity and NTU, on the optimum performance of a single-stage adsorption chiller. Silica gel–water pair was chosen as the adsorbent–adsorbate combination so that low temperature heat source under than 100 ℃could be utilized as the driving force. The mathematical model of the adsorption chiller using dimensionless parameters was developed and a global optimization method called the particle swarm optimization was applied in the simulation to obtain the optimum cycle time. The results showed that the smaller heat capacity heat exchanger improved both the maximum specific cooling capacity (SCC) and the COP. While, the larger NTU of the adsorbent bed resulted in the decrease of the COP due to the short cycle time although the maximum SCC was enhanced. The cooling effect gradually diminishes as the adsorption process progresses because the water content of the adsorbent approaches the equilibrium.

Hendrik van Heyden et al, [17] In this paper the performance of thick aluminophosphate molecular sieve layers for heat exchanger applications is evaluated. The aluminophosphate AlPO-18 (AEI structure type code) molecular sieve sorbent is coated on aluminum supports prior the sorption measurements. Two AlPO-18 samples with different morphological appearance, i.e. nano-sized crystals with monomodal size distribution and micron-sized crystals of varying sizes, are used to prepare layers with thickness in the range of 80–750μm. As a binder component, polyvinyl alcohol (PVOH) was utilized in order to prepare mechanically stable layers, which are mechanically stable over numerous measuring cycles. The sorption measurements are conducted under canonical conditions at 40℃. The AlPO-18 layers showed decreased mass flows with increasing the thickness. Additionally, the layers comprising nanosized crystals showed higher equilibrium loadings and faster kinetics compared to films based on micron-sized crystals. Following the kinetic studies of pressure, temperature and heat flow, it can be concluded that the heat transport is the rate limiting mechanism for thick aluminophosphate layers. Importantly, the diffusion limitation plays a role only for relatively thin microporous aluminophosphate layers (<200 μm). Below this thickness complete heat transfer is achieved within 2 min which allows fast heat exchanger cycles. Thus, the application of microporous aluminophosphate layers for heat transformation and storage applications is considered possible.

Conclusion

From the surveys of literature it is clear that the adsorption is very promising technology as the global warming is concern. The best utilization of waste heat is the purpose of this paper. Adsorbate need not to be pumped like vapor compression system, the amount of power saved is considerable and reduces carbon emissions. Better utilization of available solar heat or waste heat, and thereby reduction of fossil fuel consumption, sorption cooling offers several other advantages compared to conventional compression cooling. Such as reduction of summer peaks in the electricity grid, use of natural refrigerants, and low noise & maintenance. There are no moving parts here in this system so maintenance is greatly reduced. Sorption cooling, itself, is not a new development. However, the development of small scale sorption chillers (2-20 kW) is new. System is regenerative for number of cycles of operation, when silica gel is used. Amount of load on conventional chillers is reduced. Though, COP is less but amount of heating and cooling achieved, gives new direction for this type of technology.

References

[1]Research Coordinator: Takao Kashiwagi Tokyo University of Agriculture & Technology: Japan et al. “Development of Waste Heat Driven Multi-Bed, Multi-Stage Regenerative Adsorption Chiller”.

[2]Sadr Supervisor: Professor G. Wall,”Thermochemical heat pump”
[3]K.C.A. Alam et al, “Heat exchanger design effect on the system performance of silica gel adsorption refrigeration systems” International Journal of Heat and Mass Transfer 43 (2000) 4419-4431

[4]A. Rezk et al, ”Effects of contact resistance and metal additives in finned-tube adsorbent beds on the performance of silica gel/water adsorption chiller”, Applied Thermal engineering xxx(2012)1-7.

[5]C.Y. Tso et al, “Performance analysis of a waste heat driven activated carbon based composite adsorbent – Water adsorption chiller using simulation model”. International Journal of heat and mass transfer xxx (2012) xxx-xxx
.
[6]Jin Sun et al, “Heat and mass transfer during silica gel–moisture interactions”. International Journal of Heat and Mass Transfer 48 (2005) 4953–4962.

[7]K. C. Ng et al, “Experimental investigation of the silica gel- water adsorption isotherm characteristics”. Applied thermal engineering 21 (2011)1631-1642.

[8]Li Yong, K. Sumathy,” Performance analysis of a continuous multi-bed adsorption rotary cooling system”. Applied Thermal Engineering 25 (2005) 393–407.

[9]Mitsuhiro Kubota et al, “Cooling output performance of a prototype adsorption heat pump with fin-type silica gel tube module”**,** Applied Thermal Engineering 28 (2008) 87–93.

[10]T.S. Ge et al, “Experimental investigation on a one-rotor two-stage rotary desiccant cooling system”, Energy 33 (2008) 1807–1815.

[11]A. Kodama et al**,** “Use of psychometric charts for the optimization of a thermal swing desiccant wheel”. Applied Thermal Engineering 21 (2001) 1657-1674.

[12]J. Llobet, V. Goetz, “Rotary system for the continuous production of cold by solid to gas sorption: modeling and analysis of energy performance”. International Journal of Refrigeration 23 (2000) 609-625.

[13]Pascal Stabat Dominique Marchio, “Heat and mass transfer modeling in rotary desiccant dehumidifiers”. Applied Energy 86 (2009) 762–771.

[14]X.J. Zhang et al, “A simulation study of heat and mass transfer in a honeycombed rotary desiccant dehumidifier”. Applied Thermal Engineering 23 (2003) 989–1003.

[15]Ruud J.H. et al, “Waste heat driven silica gel/water adsorption cooling in trigeneration”. Applied Thermal Engineering 30 (2010) 1039–1046.

[16]Takahiko Miyazaki, Atsushi Akisawa, “The influence of heat exchanger parameters on the optimum cycle time of adsorption chillers”. Applied Thermal Engineering 29 (2009) 2708–2717.

[17]Hendrik van Heyden et al, “Kinetics of water adsorption in microporous aluminophosphate layers for regenerative heat exchangers”, Applied Thermal Engineering 29 (2009) 1514–1522.

[18]Pascal Stabat, Dominique Marchio, “Heat and mass transfer modeling in rotary desiccant dehumidifiers”. Applied Energy 86 (2009) 762–771.

[19]X.J. Zhang et al, “A simulation study of heat and mass transfer in a honeycombed rotary desiccant dehumidifier”. Applied Thermal Engineering 23 (2003) 989–1003.

[20] S.K. Henninger et al, “Cycle stability of sorption materials and composites for the use in heat pumps and cooling machines”. Renewable energy 36 (2011) 3043-3049.

[21**]**R.Z. Wang et al, “Heat transfer design in adsorption refrigeration systems for efficient use of low-grade thermal energy”. Energy 36 (2011) 5425-5439.

[22]D.C. Wang et al, “Experimental study of adsorption chiller driven by variable heat source”. Energy Conversion and Management 49 (2008) 1063–1073.

[23]C.J. Chen et al,” Study on a compact silica gel–water adsorption chiller without vacuum valves: Design and experimental study”. Applied Energy 87 (2010) 2673–2681.

[24]C.E.L. Nobrega, N.C.L. Brum, “Modeling and simulation of heat and enthalpy recovery wheels”. Energy 34 (2009) 2063–2068.

[25]S. Neti, E.I. Wolfe et al, “Measurements of effectiveness in a silica gel rotary exchanger”. Applied Thermal Engineering 20 (2000) 309-322.