Research Article

Study of adsorption refrigeration system with different working pairs

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Abstract

Absorption technologies using lithium bromide-water and water-ammonia systems are fairly well developed and have already been in use for many years. Adsorption technologies have been used extensively for separation and purification of gases for the past few decades but their exploitation for refrigeration and heating purposes is rather recent. The advantage of adsorption cooling system is that they can be driven by low-grade energy such as waste heat or solar energy. In an adsorption refrigeration system, the critical component is sorption bed where adsorption and desorption of adsorbate from adsorbent take place. Effective performance of an adsorption refrigeration system depends on how effectively desorption and adsorption occur at selected temperatures. It is planned to study desorption and adsorption characteristics of different working pairs theoretically. It is expected that this study would help to identified right working pairs suitable for particular applications and operating conditions. In this project, a thermodynamic analysis of sorption bed has been carried out.

Introduction

Refrigeration becomes an indispensable part of modern life next to electricity for meeting many human requirements and maintaining high standard of living. Starting from domestic utilities for preservation of food, it finds its wider applications ranging from commercial and health-care outlets to larger industrial establishments for safeguarding perishable goods and commodities besides comfort air-conditioning. According to thermodynamic principle, any cooling system necessitates an external source of motive energy to transport heat from lower temperature space to higher temperature region [1]. This actuating energy can either be a high-grade energy such as electricity, mechanical work etc. or low-grade energy such as thermal energy. Thus, a refrigeration system is identified as work-operated system or heat-operated system [2].

A simple adsorption refrigeration system consists of an adsorption bed, evaporator, capillary and condenser. In fact, this sorption bed, thermally compresses desorbed vapour to condenser pressure similar to the compressor of a vapour compression refrigeration system.

Adsorption refrigeration cycle is executed through four processes being carried out individually in each component of the system [3]. Refrigerant vapour from the evaporator is adsorbed by adsorbent at a low temperature corresponding to evaporator pressure. When the temperature of adsorbent reaches the desorption temperature due to heat of, say, solar energy, the adsorbate begins to evaporate from the bed. Thus the adsorbed vapour is driven out using solar radiation falling on the collector. The vapour from the collector is sent to the condenser where the conversion of vapour to liquid occurs [6]. Subsequently the liquid refrigerant is stored in a storage tank kept below the condenser. Indeed the high pressure liquid from the storage tank is passed through capillary tube to create low pressure at the evaporator inlet. Thus, the operation of system cycle is executed intermittently in the vapour adsorption cooling system [8].

Materials and methods

The present work on vapour adsorption refrigeration is motivated by two factors. Firstly, the chloro-fluoro refrigerants left into atmosphere impair the stratospheric ozone

umbrella and subsequently give way for hazardous ultraviolet rays to reach the earth's surface and also, cause global warming. It is noteworthy to bring forth that every refrigerant in the families of CFCs and HCFCs has been implicated as a cause of depletion of ozone layer and as a potential source for global warming. With a view to protect the environment and the living beings on this earth, efforts have been taken to implement the task of phasing-out gradually all CFCs and HCFCs on the basis of the Montreal and subsequent International Protocols. Hence there is a shift towards thermally driven refrigeration systems. R.Z Wang et.al [1] conducted experimental study for ice making using activated carbon and ethanol. Naidal H [2] explained optimal design parameters for solar adsorption system. Activated carbon and ethanol pairs are exprementally conducted by many authers [3-5] .By using industry exhaust gas as input energy Zeolite and water pairs are used using the temperature range of 250 to 450 degree centigrade [6,7]. A three dimensional non equilibrium model which take into account for both internal and external mass transfer [8]. Limitations of adsorption system is evaluated by the authors in [9-11].

Numerical results on operating parameters influence for a heat recovery adsorption machine was done by [15]. Bed design and cooling power identification using adsorption system is evaluated by the authors [16,17]. Metal–Organic Frameworks as potential adsorbents for solar cooling applications [21]. Thermal performance of a vapour adsorption refrigeration system compared to the other pairs theoretically evaluated performance of the system.

Adsorption is selective binding of a substance by another solid substance. The adsorption process occurs at solid- liquid, solid-solid, gas- liquid or liquid- liquid interfaces. Evan though the adsorption process is similar in all cases, the forces of attraction between the adsorbate and adsorbent is different in each case [8]. Based on the forces of attraction between the adsorbate and the adsorbent, the adsorption process, can be classified as follows:

- Physisorption
- Chemisorption

The forces active in physical adsorption are electrostatic in nature and occur under suitable conditions in most gas-solid systems. These forces are present in all states of matter: gas, liquid, and solid. They are the same forces of attraction that cause gases to condense and deviate from ideal behaviour under extreme conditions. Physical adsorption is also referred to as van der Waals' adsorption.

Because of Vander Waals' forces, physical adsorption can form multiple layers of adsorbate molecules, one on top of another. Physical adsorption can result from three different effects: orientation, dispersion, or induction. For polar molecules, attraction occurs because of the orientation effect. The adsorption of a non- polar gas molecule onto a non- polar surface is accounted for by the dispersion effect. The attraction between a molecule with a permanent dipole (polar molecule) and a non-polar molecule is caused by the induction effect [9].Physisorption is a reversible process because the forces holding the adsorbate and adsorbent is very weak and desorption readily occurs. The heat given off by physical adsorption is much lower, approximately 0.1 kcal/g- moles, which is comparable to the heat of condensation.

Chemical adsorption (chemisorption) results from a chemical interaction between the gas and the solid. The gas is held to the surface of the adsorbate by the formation of a chemical bond. Adsorbents used in chemisorption can be either pure substances or chemicals deposited on an inert carrier material [10]. Chemisorption is an irreversible process. Molecules that are chemisorbed are very difficult (and, in some cases, impossible) to remove from the adsorbent surface. Either increasing the operating temperature or reducing the pressure of the adsorbent bed can usually remove physically adsorbed molecules. Chemisorption stops when all the active sites on the surface of the adsorbent have reacted, forming only a monolayer of adsorbate molecules on the surface. In chemisorption, the heat of adsorption is comparable to the heat evolved from an exothermic chemical reaction, usually around 10 kcal/g-moles.

The objectives and scope of the present work are: To perform a thermodynamic analysis of solar assisted adsorption refrigeration system with environment-friendly refrigerants [12].

- To study experimentally the performance of the adsorption refrigeration system with few working pairs and to demonstrate the viability and suitability of the selected pairs
- To compare experimentally evaluated performance of the system with simulated results

Adsorption pair means the pair which consists of adsorbent and refrigerant. The adsorption working pair is the vital part in the adsorption refrigeration cycle. The selection of any pair of adsorbent–adsorbate for refrigeration applications depends on certain desirable characteristics of their constituents. These characteristics range from their thermodynamic and chemical properties to their physical properties and even to their costs or availability. The adsorbate or refrigerant is required to have the following properties for efficient performance:

- Evaporation temperature below 0 °C.
- Small molecular size to enable it to be adsorbed into the adsorbent.
- High latent heat of vaporization and low specific volume.
- Thermally stable with the adsorbent at the cycle operating temperature ranges.
- Non-toxic, non-corrosive and non-flammable.
- Low saturation pressures (above atmospheric) at normal operating temperature.

They have further presented important points to be considered for the choice of a suitable adsorbent as,

- Adsorption of large amount of adsorbate under low temperature conditions.
- Desorption of adsorbate when exposed to high temperature source.
- Possession of high latent heat of adsorption compared to sensible heat.
- No deterioration with age or use.
- Non-toxic and non-corrosive.
- Low cost and widely available.

A refrigeration system thermodynamically requires an external power to transfer heat from cold source to hot surrounding. This is evident from the operation of vapour compression refrigeration system wherein a vapour compressor imparts work to

effect refrigeration. An adsorption refrigeration system also operates like a vapour compression system except that the compressor is replaced by sorption bed which is known as thermal compressor. Unlike vapour compression system which is actuated with high grade energy, the adsorption refrigeration can be operated with low grade energy such as solar energy. This chapter includes the description of the solar adsorption refrigeration system, its thermodynamic cycle, assumptions made in the analysis and computational procedure involved in the development of computer code. The system consists of a sorption bed, condenser, liquid storage tank, expansion device and evaporator. The adsorbent in powder form is packed in the sorption bed. Refrigerant vapour from evaporator is adsorbed by adsorbent during sun-off period. This vapour is desorbed due to heat received from sun during day cycle. The desorbed vapour enters condenser where it is converted to liquid. The liquid refrigerant travels back to evaporator after passing through an expansion device.

On receipt of heat to the sorption bed, isosteric pressurisation occurs initially that makes the vapour pressure increase from the evaporation pressure up to the condensation pressure. Subsequent addition of heat leads to desorption followed by condensation. The refrigerant in liquid form flows to evaporator at which isosteric depressurisation occurs, when the adsorber releases out heat that leads to cooling. As the adsorbent temperature drops, the vapour pressure is lowered down to the evaporation pressure. Thus, as the adsorber continues releasing heat, refrigerant is evaporated and adsorbed by adsorbent in the adsorber [14].

The adsorption refrigeration cycle depends on the adsorption of a refrigerant vapour by the adsorbent at low pressure (evaporator pressure) and temperature and subsequent desorption by heating at high pressure (condenser pressure). Satisfactory performance of adsorption refrigeration relies on working pairs chosen on the basis of application, availability and locality where refrigeration is required. Hence right selection of adsorbent-adsorbate pair becomes essential to meet the required demand. Adsorbents commonly available are activated carbon, silica gel, zeolite,

and calcium chloride. Activated carbon is a non-graphite form of carbon which could be produced by pyrolizing and carbonizing source materials, such as coal, lignite, wood, paddy husk, coconut shells and synthetic polymers at high temperatures (700 to 800° C). Activated carbon available in many forms including powders, micro-porous, granulated, molecular sieves and carbon fibre. Generally, the activated carbon in the powder form (15 to 25 µm particles) is used for adsorption liquids [15]. Activated carbon manufactured from coconut shell is considered superior to those obtained from other sources mainly because of small macro pores structure which render it more effective for the adsorption.

Silica gel is a chemically inert, nontoxic, polar and dimensionally stable. It is an amorphous form of (SiO_2). It is prepared by reaction between sodium silicate and sulphuric acid followed by a series of treatment process such as agening, pickling .It contain large adsorption capacities widely used for dehumidification process. Zeolite are natural or synthetic aluminium silicates which form a regular crystal lattice and release water and high temperature. It is a polar in nature manufactured by hydrothermal synthesis of sodium aluminosilicate is an autoclave followed by ion change with certain cationic. It is mostly used for drying and separation of hydrocarbon mixtures. Calcium chloride is a very widely available adsorbent that remain solid until saturated beyond which it dissolves in water but can still be used as a low temperature liquid desiccant. It also has good potential for use as a solid chemical adsorbent for methanol and ethanol vapour [15].   The need to eliminate environmentally malignant refrigerants dictates right choice for wider use. It is a generally refrigerants such as ammonia, water, methanol, ethanol, sulphur dioxide and other refrigerant like R134a, R141b, R152a, R600a.

Ammonia is a compound of nitrogen of and hydrogen with the formula NH_3 at standard temperature and pressure ammonia is a gas. It is toxic and corrosive to some materials and has a characteristics pungent odour. Ammonia used commercially is called anhydrous ammonia to distinguish is from ammonium hydroxide solution.

Methanol also known as methyl alhocol or wood alcohol is a chemical compound with chemical formula (CH_3OH).It is the simplest alcohol, and is a light, volatile, colour less, flammable, poisonous liquid with a distinctive odour. It is produced naturally in the anaerobic metabolism. Methanol is oxidized by oxygen with the help of sunlight to carbon dioxide and water. Ethanol also known as ethyl alcohol or grain alcohol is a flammable, tasteless, colourless, mildly toxic chemical compound with a distinctive odour. This the alcohol found in alcoholic beverages. It is often referred to simply as alcohol. Its molecular formula is (C_2H_6O).

Water is abundant in nature. It can take many forms. The gaseous state is known as vapour or steam and the common liquid phase is generally taken as simply water [16].

Adsorption is the process of attraction of an organic or inorganic vapour called as adsorbate to the surface of a solid known as adsorbent. Since adsorption is a surficial phenomenon, it is obvious that larger the exposure area of the adsorbent be, better will be the adsorption of adsorbate. Thus adsorption is influenced predominantly by physical properties and nature of adsorbent in addition to chemical properties of adsorbate in association with adsorbent. The physical parameters that affect adsorption are porosity, pore size and granular size of adsorbent.   The adsorbent porosity measures the free spaces (voids) inside the adsorbent granule and is given as the ratio between the voids volume over the total volume. The heat transfer and the refrigerant concentration are influenced with adsorbent porosity. As the adsorbent porosity increases the adsorption capacity increases and with time the adsorbent becomes saturated, hence the adsorption rate decreases with time. The cycle time should be within the time period of high adsorption kinetics, otherwise the cycle performance deteriorates. Inversely, the adsorbent thermal conductivity decreases as adsorbent porosity increases and hence the adsorption kinetics (adsorption rate) also decreases. When the pores size reduces the adsorbent porosity increases. This results in increase of the adsorption specific surface area of the granule. In fact, the smaller the pore diameter, the higher is the adsorption isosteric

energy and subsequently the regeneration temperature increases. One of selecting criteria of the suitable working pair is the compatibility between the pore size and refrigerant vapour molecules average diameter. If the pore size is too small to accommodate the vapour, the adsorption kinetics will be significantly reduced. The granules size affect both of heat and mass transfer of the adsorbent bed. Decreasing the adsorbent granular size reduces the contact thermal resistance between the granules and heat exchange surface. The heat transfer continuity through the adsorbent bed of small granules size is higher than that of large granules. This is due to the reduction of voids between granules. There are two types of mass transfer resistances in adsorbent bed: the first is the mass transfer within the adsorbent granules (intra-particles) and the second is the mass transfer through the voids between the granules (inter-particles). The intra-particle mass transfer of small granules is higher than that of large granules. This is because the total surface area of the bulk granules is higher for the smaller size. The adsorbent bed of large granules size (larger voids) has higher permeability level and hence better inter-particle heat transfer performance, which is more critical for refrigerants requiring very low evaporative pressure [13].

The analysis of a vapour adsorption system includes the optimisation of the operating parameters in order to obtain maximum coefficient of performance. The first step involves the calculation of the mass flow rate of the refrigerant. The mass flow rate of the refrigerant can be calculated using the capacity of the refrigeration system which is known and the refrigeration effect obtained by the system [4].

The complete operation of vapour adsorption refrigeration system rests on two vital processes, namely, the heating process (desorption) and the cooling process (adsorption).The basic cycle of adsorption-desorption consists of four processes: isosteric heating (a-b), isobaric desorption (b isosteric cooling and isobaric adsorption. Heat supplied through solar energy to sorption bed contributes initially in sensible heating of adsorbent during which desorption of vapour seldom occurs. However, this sensible heating helps in isosteric pressurisation from evaporator pressure to condenser pressure. On reaching condensation pressure, refrigerant vapour starts dissociating from adsorbent due to further heating. Thus, concentration of refrigerant vapour increases from minimum to a maximum value during desorption process. The value of concentration can be estimated using D-A equation [4] expressed in terms of temperature of the bed as,

$$M_x = M_0 \exp\left[-k\left(\frac{T}{T_{sat}} - 1 \right)^n \right] \quad (1)$$

where the exponent n describes the surface heterogeneity and k relates to affinity coefficient. The heat associated with sensible heating during the process a-b is expressed as,

$$Q_{ab} = \int_{T_a}^{T_b} \left(C_{p_{Ad}} + M_{max} C_{p_r} \right) dT \quad (2)$$

The heat associated with desorption of refrigerant from adsorbent during the process b-c, is expressed as,

$$Q_{bc} = \int_{T_b}^{T_c} \left(C_{p_{Ad}} + M_x C_{p_r} \right) dT + \int_{M_{min}}^{M_{max}} H \, dM \quad (3)$$

In the above expression, the heat corresponding to phase heating of desorbing refrigerant is approximated as,

$$H = R\left(C_{p_{Ad}} + M_x C_{p_r} \right)\left(\frac{T}{T_{sat}} \right) \quad (4)$$

Total heat required for heating the adsorbent and stripping off refrigerant is estimated as,

$$Q_g = Q_{ab} + Q_{bc} \quad (5)$$

Further, M_{max} and M_{min} can also be computed using D-R equation corresponding to adsorption and desorption temperatures.

The cooling capacity of

$$Q_r = m_r.\left(M_{max} - M_{min} \right).\left(h_{evp} - h_{con} \right) \quad (6)$$

The coefficient of performance of single adsorbent bed can be estimated as the ratio of total refrigeration capacity of the system to the total heat supplied to the system. For theoretical analysis, the system performance is compared by two parameters, namely, Carnot COP and theoretical COP.

The Carnot COP is presented as,

$$COP_{Carnot} = (T_{des} - T_{ad} / T_{des}) (T_e / T_{con} - T_e) \quad (7)$$

The theoretical COP is expressed as,

$$COP = \frac{Q_r}{Q_{12}+Q_{23}} \quad (8)$$

$$SCE = (x_{max} - x_{min}) (L- Cp_{ref.}(t_c-t_e)) \quad (9).$$

Result and discussion

Activated charcoal-methanol as a pair used in adsorption refrigeration system. The operating variables are desorption temperatures varies from 85 to 100^{0}C. Adsorption range is to 120^{0}C take place a cycle time. Adsorption and desorption performance curves are a shown in figure.

Fig. 1 shows the effect of desorption temperature on volume of methanol desorbed. It is observed that volume of desorbed methanol increases with increase in desorption temperature. It can be justified that, at higher temperature porosity of the adsorbent powder increases and hence more gaseous methanol is driven out of the sorption bed. Fig. 2 illustrates the influence of adsorption temperature on volumetric quantity of methanol being adsorbed. Since adsorption is an exothermic reaction, higher temperature at the sorption bed decelerates the adsorption of adsorbate by adsorbent. This leads to decrease in mass of methanol being adsorbed when adsorption temperature increases. Fig. 3 shows the effect of desorption temperature on amount of water desorbed. It is observed that amount of desorbed water increases with increase in desorption temperature. It can be justified that, at higher temperature porosity of the adsorbent powder increases and hence more gaseous water is driven out of the sorption bed.
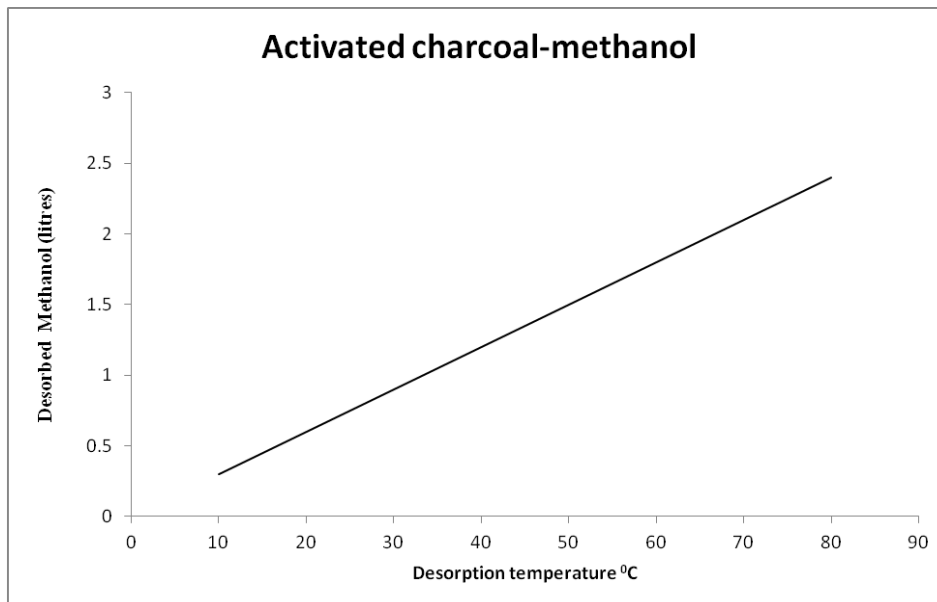

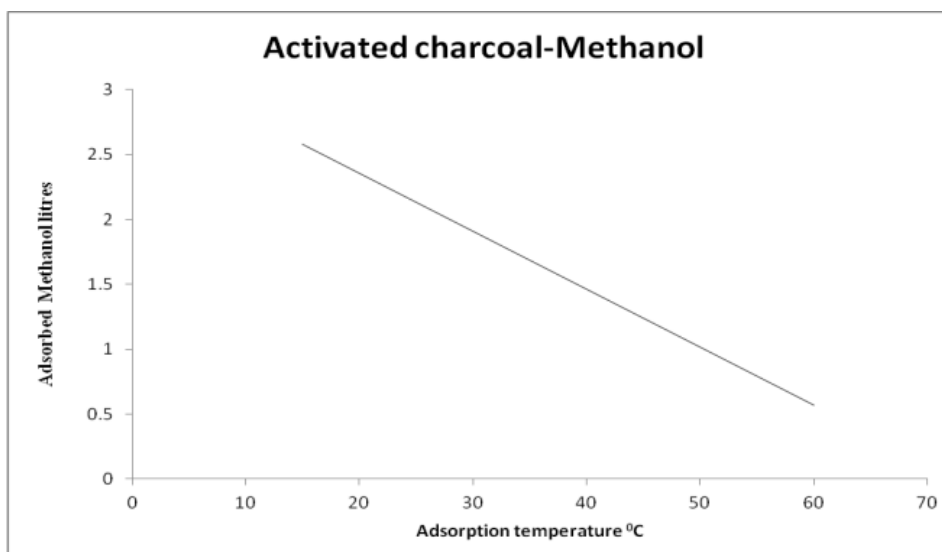Fig. 1. The variation of desorption temperature with desorbed methanol

Fig. 2. The variation of absorption temperature with absorbed methanol

Fig. 4 illustrates the influence of adsorption temperature on amount quantity of water being adsorbed. Since adsorption is an exothermic reaction, higher temperature at the sorption bed decelerates the adsorption of adsorbate by adsorbent. This leads to decrease in mass of water being adsorbed when adsorption temperature increases. Fig. 5 indicates COP vs different pairs. Zeolite water shows low COP due to thermo – physical properties.
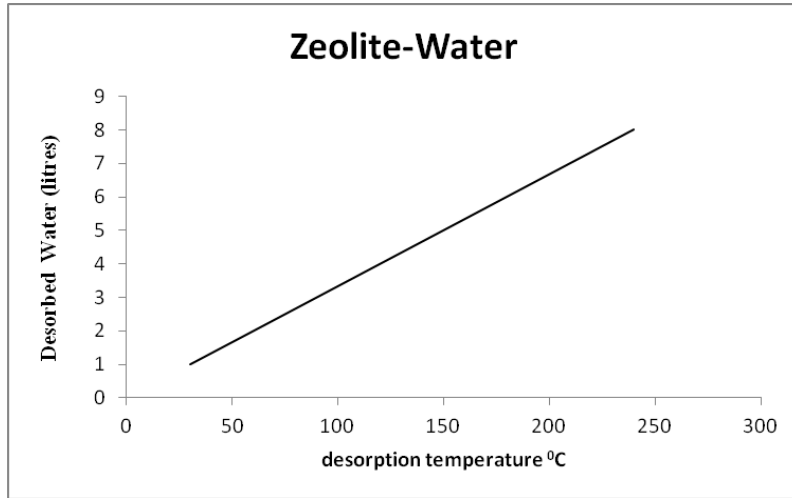

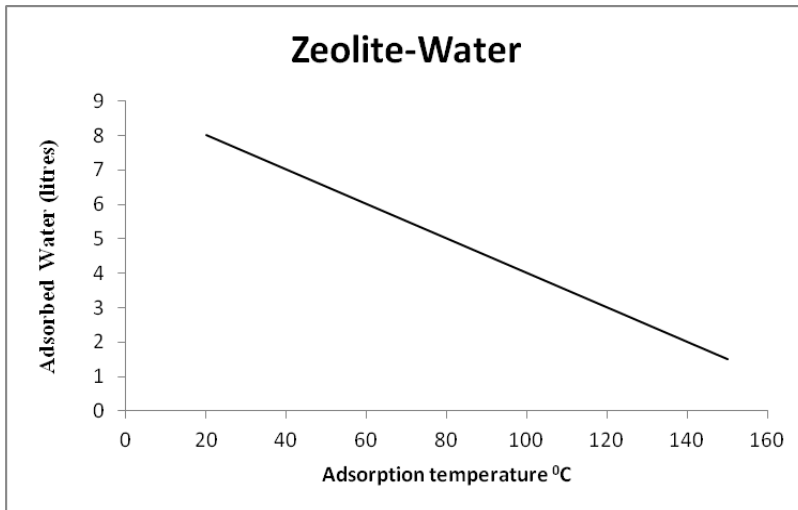Fig. 3. The variation of desorption temperature with desorbed water

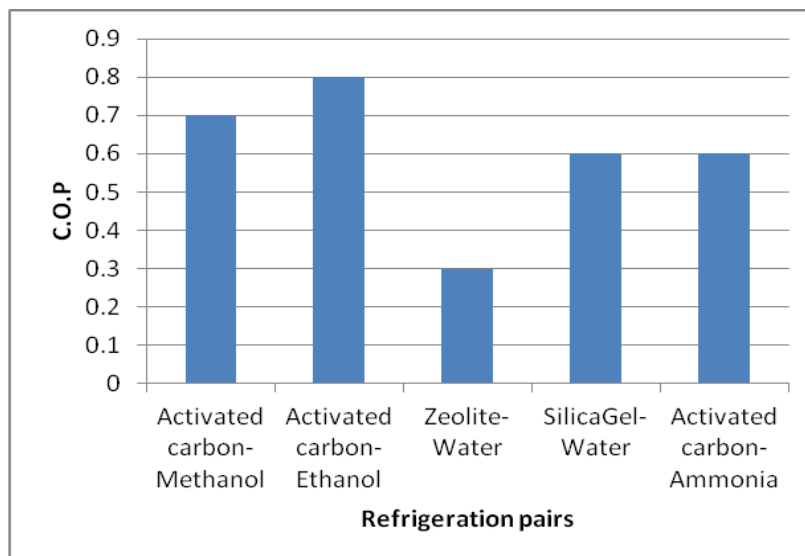Fig. 4. The variation of desorption temperature with desorbed water

Fig. 5. The variation of refrigeration pairs with COP

Conclusions

Performance analysis of the adsorption refrigeration was carried out different working pair with different operating condition, like a desorption and adsorption temperature ranges of pairs are identified. A detailed thermodynamic model analysis has been developed for the solid adsorption refrigeration system. In this analysis relatively simple equations based on the representation of Dubinin–Astakhov with the help programming method to calculate the mass of adsorbent / adsorbate required level can be desired and specified the activated carbon – methanol as a adsorptive pair and also mention the different pair with environmental characteristics are obtained.

Conflict of interest

Authors have declared no conflict of interests.

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