Studies on the feasibility of adsorption cooling technologies

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Abstract. In the current scenario, for majority of the people and industry needs of the globe, cooling processes such as refrigeration as well as air conditioning are important and major requisites. On the other hand, the conventional vapour compression systems require high electrical energy input and employ refrigerants with negative environmental impacts like ozone layer depletion and climate change resulting from the emission of harmful gases such as CO_2, Hydro fluorocarbons and Chlorofluorocarbons with the usage of conventional refrigerants. The solar energy being a renewable source is one of the key solutions to pollution problems and can be used to drive the adsorption cooling machines. With the heat source temperature of even 50^0 C which is obtained from the low grade energy like solar energy or waste heat energy is feasible to run the adsorption refrigeration system to reduce the operating cost. In the present work, a single bed adsorption refrigeration system is developed and tested using working pair as silica gel and water. From the experimental results, it was observed that this system can be used as alternative to the conventional vapour compression refrigeration system to produce cooling effect. However, the performance of the adsorption system studied is lower than the vapour compression refrigeration system.

1. Introduction

The demand for a comfortable indoor environment has increased day by day proportionate to the growth of standards of living of the people. Consequently, it has taken a way for the significant increase in the utilization of electricity in air conditioning, heating and ventilation. The electrical energy input required for both commercial as well as domestic sector in case of air conditioning is demanding for the supply of more electricity, especially in the peak periods. In dry and hot areas, it is evident that major energy consumption of a building is used to fulfil the thermal comfort in the indoor atmosphere which is normally achieved by traditional air-conditioning techniques that utilizes as high as 70% of total building energy consumption. However, vapour compression system is ideal due to its higher coefficient of performance, adaptability and compactness in manufacturing and operation but demands high extent of consumption of primary energy sources which leads to electricity peak loads and refrigerants employed are harmful to the environment and results in ozone layer depletion and global warming because of the emission of unfavourable gases such as carbon dioxide, Hydro fluorocarbons and Chlorofluorocarbons with the usage of traditional refrigerants. Obtaining cooling with the use of green and clean energy similar to solar energy is the acceptable means of solving the issues such as electricity and pollution. Hence, an alternative way to the present cooling methodology is necessary.

Solar driven solid adsorption is a technology which has taken considerable interest since 1990s owing to its environmentally friendly nature, being noise free and energy free. In the latest decades, research related to solar assisted adsorption refrigeration has been carried out appreciably, which focussed on finding new working pairs, suggesting advanced thermal cycles, and design of prototypes. Through such attempts the system performance in terms of COP has been improved appreciably. However due to the increased complexity of advanced cycles(e.g. cycles with heat and mass recovery) and natural feature of solar power, these sorts of systems face two major limitations , namely the lack of working reliability due to the issue of long term vacuum keeping and paucity of a reliable heat source in poor weather conditions.

With the investigations related to adsorption cooling, variety of adsorbent and adsorbate combinations have been used and compared. Using the working pairs such as silica gel-water, zeolite-water, silica gel-methanol, activated carbon-methanol and activated carbon-ammonia significant research has been done. Based on the comparative studies, it has been considered that the combinations of activated carbon-methanol and silica gel-water are identified as two good pairs suitable for the systems that can be driven with low values of temperature and these two combinations can normally be powered with an heat source temperature below 100^0C, where as the working pair with zeolite normally requires the heat source temperature to be around 200^0C

Significant interest is shown on adsorption cooling systems since few decades to meet the societal needs of cooling systems and to manage the present environmental issues. The major attraction towards cold production by the technology of adsorption refrigeration is that it can be driven fully or partly by making use of the low grade energy like waste heat and solar energy with temperature of heat sources starting from 50^0C. Hence it is treated as possible substitute to the traditional refrigerator which works on vapour compression principles, especially in the distant places of the world where there is no accessibility to the utility grid. On the other hand, the COP achieved with solar driven adsorption system is slightly low in comparison with the existing system which may be due to the insufficient research and improvement in the system. Hence, it is required to improve the performance of the system with higher COP. For the development of such an economical system with good COP, the design aspects of solar energy collector and choosing adsorbent and refrigerant materials acceptable for these systems is a significant feature for solar cooling techniques.

1.1 Introduction to adsorption

Adsorption is a surface phenomenon where the particles called adsorbate sit on some other surface called adsorbent and the process occurs at the interface of two phases [1-2]. The process happens owing to the mutual attraction of molecules of one substance with each other. The adsorbing entity is called as the adsorbent which is normally in a solid state, the material adhered is named as the adsorbate or refrigerant which is usually a fluid or a gas. The adsorption is accompanied by the release of heat and the process is exothermic [3]. The quantity of heat evolved depends on the magnitude of forces of cohesion and the latent heat of condensation of the refrigerant. Normally the heat of adsorption of refrigerant is several times greater than the heat of condensation [2]. Hence, when a dry adsorbent and adsorbate in a liquid state coexist individually in an enclosure, the adsorbate molecules gets adhered onto the outer skin of the adsorbent material in the form of vapour instead of a liquid phase. The process of evaporation consumes the heat from the liquid refrigerant and the adsorption heat will be produced in the adsorption process. In such a manner, the liquid refrigerant will decrease in its temperature whereas the adsorbent's temperature will increase. This is the principle used in adsorption system to achieve cooling.

1.2 Principle of adsorption cooling

An adsorption cooling system of single bed type is schematically represented in figure 1. Generally it has a condenser, evaporator, adsorber-desorber bed filled with the adsorbent and an expansion valve. The thermodynamic cycle can be completed with four operations namely, pre-heating, desorption, pre-cooling and adsorption. During pre-heating, the bed and the evaporator is isolated and adsorption bed is subjected to heating with available heat source, which increases the bed pressure. The moment where the adsorbent bed pressure exceeds than that of the condenser, the refrigerant find its way to the condenser and the process of desorption begins. Refrigerant vapour is regenerated from the adsorbent bed due to additional heating and enters into the condenser and gets condensed. As the desorption process is completed, the bed and the condenser is disengaged and adsorber bed is circulated with cooling water and that is the process known as pre-cooling which decreases the bed pressure and becomes less than that of the evaporator. During this, the adsorber bed is connected to the evaporator and evaporated refrigerant vapor comes out of the adsorber and is adsorbed in the adsorbent bed. During the adsorption process, bed is cooled continuously to dissipate the heat of adsorption.The variation of pressure and temperatures during the cycle of operation are shown in figure 2.

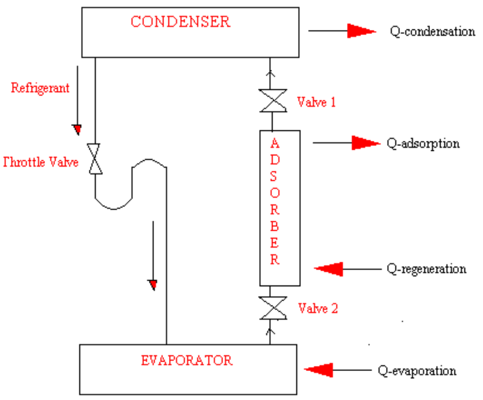

Figure 1. A typical adsorption cooling system

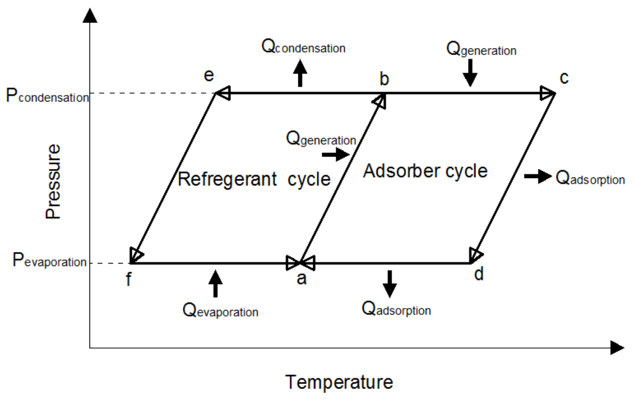

Figure 2. P-T curve of Adsorption cycle

1.3 Adsorbent-refrigerant pairs

In an adsorption cooling, adsorption pair involves adsorbent and refrigerant or adsorbate and is mainly classified into physical, chemical or composite adsorption working pairs. Choosing any combination depends on some desirable properties of their constituents, their chemical and thermodynamic behavior and also the availability and cost involved. The different combinations which are commonly used in practice are shown in Table 1.

Table 1. Adsorbent-Refrigerant pairs [17]

Adsorbent	Adsorbate
Silca Gel	Water
Silca Gel	Ammonia
Zeolite	Water
Activated Carbon	Methyl Alcohol
Activated Carbon	Ethyl Alcohol
Calcium chloride	Ammonia
Metal hydrides	Hydrogen
Metal Chlorides	Ammonia

2. Literature review

The following section of this literature review highlights the efforts made to achieve cooling by adsorption and its related studies.

Using silica gel and water an adsorption cooling system was designed and studied aiming to reduce the manufacturing costs as well as to make simple construction. The heat transfer area was increased using a flat-tube type heat exchangers and it is reported that the cooling can be achieved and the obtained COP and specific cooling power was 0.45 and 176W/kg respectively. [4]

A study was made to obtain 7°C of chilled water outlet temperature using single stage chiller of conventional and two bed type by making use of silica gel and water. From the experimental results, it is reported that for a cycle time of 1100 sec and collector area of 38.64 m^2 better performance is achieved with 7°C. However the influential parameter for an adsorption cooling system is the rate of flow of chilled water. Also it is reported that the maximum value of COP is 0.5. [5]

In a study, with a system input temperature of 82.5°C, a COP of 0.39 and 12°C of chilled water is produced where the combination of silica gel and water is employed along with a methanol evaporator for the purpose of cooling.[6]

With the use of heat pipes, several novel ideas were presented and the first attempt of such type was a small scale water chiller using silica gel adsorbent with water and the rated cooling power as 10 kW, COP achieved was 0.4 when the driven temperature of the system was hot water of 85^0C. The next example is a air conditioner operated by 80^0C hot water using silica gel–water combination with an achieved COP of about 0.3. The another attempt is with the use of split heat pipes in order to heat or cool the adsorbent bed for ice manufacturing in fishing boats. It is reported that, these kinds of technologies keep away the adsorber corrosion during the heating stage by exhaust gases and during the cooling process by sea water. [7]

In an experimental study on a compact silicagel-water adsorption chiller, silica gel with microspores diameter from 0.5 to 1.5mm was used. A novel heat recovery and the mass recovery techniques were adopted for improving the COP. The COP was 0.49 and 9.60 kW was the cooling power when 82^0C and 12.3^0C were the driving temperature and outlet temperature of chilled water respectively. The optimal cycle time was 720s, mass recovery-like time was 80s and time of heat recovery was 20s. [8]

A cooling power of 3.6kW, specific cooling power of 208 W/kg and a COP value of 0.62 were reported in a study based on silicagel and water pair adsorption cooling of waste heat driven type. [9]

In a study made on adsorption performance deterioration on silicagel-water adsorption cooling it was observed that there are many parameters to affect the performance of adsorption using silicagel and the pollution was the major cause for the decrease of capacity of adsorption. On the other hand, the performance of adsorption was explored with deteriorated samples after they are being processed with the help of acid solution to find out the possible routes to recondition the performance of adsorption. [10]

In a performance study of adsorption air conditioner using zeolite-water, 8–12^0 C chilled water was obtained from the conditioner to be supplied to the fan coil and where system was driven with a temperature of 350–450^0C of exhaust gas. The achieved COP and refrigerating power were 0.25 and 5kW. The power of the refrigerating machine was upto10 kW and the SCP reached to 200W/kg with 6.5^0 C of evaporating temperature for the cycle time of 1320 seconds. [11]

In a mobile adsorption air conditioner, by employing zeolite-water pair with the use of double adsorption bed, the COP of 0.4 and SCP of 600 W/kg were achieved. [12]

With a cycle time of 56 minutes, a performance coefficient of 0.125 and SCP of 16 W/kg was achieved in a system using solidified activated carbon adsorbent and methanol refrigerant.[13]

With activated carbon-Methanol pair, a prototype was developed and per m^2 area of solar panel 6 kg of ice was made with an achieved C.O.P of 0.12.[14]

Using an heat source temperature of about 60 to 95^0 C, A COP of 0.6 was achieved with a cycle time of 600–700 seconds in an adsorption system where activated carbon fibres and ethanol pair was employed. [15]

It is reported that the cooling capacity of 12kW can be obtained with an adsorption cycle when the temperature of heat source is about 85^0C with activated carbon of fibre type and ethanol combination in a simulation program made for evaluating the performance of adsorption cooling of solar driven type by taking into account the meteorological data of Kaula lampur of Malaysia. The Results also revealed that the adsorption cooling is feasible to achieve with heat source of low temperature. [16]

3. Experimental setup

Adsorption is a surface phenomenon, in which cooling effect is achieved by the accumulation of adsorbate on the surface of porous adsorbent material. In the cooling system by adsorption the compressor of VCR system is replaced with an adsorber cum desorber to achieve the functions of compressor. The experimental setup is shown in figure 3 and details of different parts of the adsorption cooling system are discussed in the following section.

Figure 3. Single bed Adsorption Cooling System

The system consists of three vacuum chambers viz, adsorber, condenser and evaporator and all are mounted on the same frame to establish an adsorption or desorption. Along with these three vacuum chambers there are many other components which are present in an adsorption cooling system, namely vacuum pump, circulating pump, vacuum gauges, solar water heating system, overhead tank, bypass storage tanks, copper tubes for carrying adsorbate, ball valves, solenoid valves, temperature sensors, temperature indicators etc.

3.1 Experimental procedure

Vacuum is achieved initially in the adsorbent reactor and evaporator is isolated. When the water temperature becomes 10°C close to desired temperature value, the water pump is made on, flow control valve is closed and bypass valve is kept open. The water temperature decreases since the pump, tubes and valve temperatures are lower than hot water temperature. The flow control valve is opened, when the water tank temperature is raised again over the optimum value to start the regeneration of adsorbent bed. The water flow rate is regulated using the flow control valve as well as the bypass valve. The reactor is continuously heated and the reactor pressure is increased moderately by opening the drain line to achieve condensation of the refrigerant vapour to be collected through the drain line. The last step is repeated to ensure the dryness of the adsorbent bed reactor. The water control valve is closed then the pump is turned off followed by draining the water tank and then filling with cold water from the supply mains. The water pump is made on, while the bypass valve is fully open. Within a short span of time the flow becomes stable and the flow through the adsorbent bed. The required flow rate is controlled by the flow control valve and bypass valve. The adsorbent bed is pre-cooled for few minutes and subsequently the refrigerant flask is connected to the adsorbent bed to start the adsorption process. During this process the connection line including the connection valve temperatures are maintained at about 10°C higher than the refrigerant temperature to prevent condensation of water vapour. During the pre-cooling and adsorption process the vacuum pump is turned on. After the adsorption period for the definite sorption time, flask having the refrigerant is set apart, flow control valve is fully closed, and vacuum pump as well as secondary flow pump is shut down.

3.2 Experimental observations

The experiment was conducted with the working pair as silica gel and water. Using vacuum pump, the system pressure was brought down to vacuum condition at the beginning of each trial. The experiment is conducted by keeping 20ml of water in the evaporator and at three different hot water (Desorption) temperatures. The decrease in temperature in the evaporator with cycle time is noted down and COP is calculated. The table 2 shows the observations during the experiment. The experiment is repeated with hot water supplied to the adsorber at different temperatures from 60^{0}C to 80^{0}C with an increment of 10^{0}C and COP is calculated.

Table 2. The values of COP achieved with different desorption temperatures

Water in evaporator ml	$P_{evaporator}$ mm of Hg	$P_{adsorber}$ mm of Hg	$P_{condenser}$ mm of Hg	Hot water temperature ^{0}C	Lowest temperature observed in the evaporator ^{0}C	Adsorption/ desorption phase time in minutes	COP
				60	16.5	16	0.51
20	665	680	680	70	14.3	16	0.66
				80	13.2	16	0.67

3.2.1 Variation of evaporator temperature and COP for different hot water temperatures with respect to time for 20 ml of water in the evaporator.

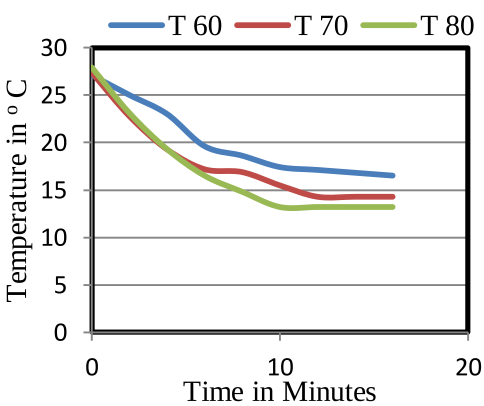

Figure 4. Evaporator temperature v/s Time

The reduction in temperature due to adsorption/desorption cycle with respect to cycle time is shown in the Figure 4. From the graph, it is evident that, the evaporator water temperature decreases as the heat source temperature increases and the lowest value of temperature is observed for the heat source temperature of 80^{0}C.

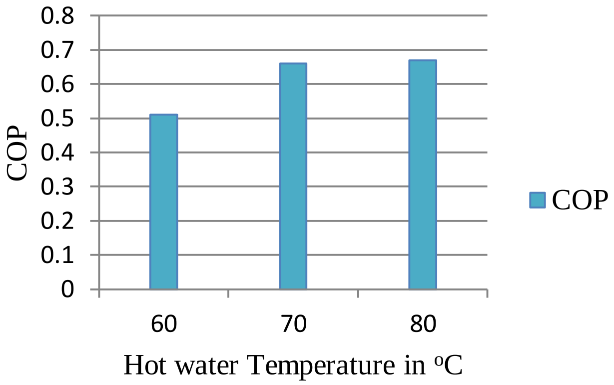

Figure 5. COP v/s Hot water temperature

Figure 5 shows that the value of COP increases with increase in heat source temperature and highest value of COP is observed for 80^0C and the reason could be the COP depends greatly on the heat source temperature available.

4. Conclusions

The following are the conclusions drawn from the study.

1. It is necessary to maintain vacuum pressure for the phenomenon of adsorption to occur and optimum value of vacuum pressure has to be maintained to enhance the process of adsorption and thereby its performance.
2. During desorption cycle, the adsorbate regeneration can be achieved even at a temperature around 60^0C and cooling effect can be produced in the evaporator.
3. COP increases with increase in heat source temperature
4. It is feasible to produce low temperature effectively by an environmental friendly system using silica gel bed for adsorption/desorption of water which has no harmful environmental impact.

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