Performance Evaluation of Solar Assisted Adsorption Water Chiller with Silica gel-Water as Adsorbent-Adsorbate Pair

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Abstract— **The economic development plant implemented since independence have necessarily required increasing amounts of energy. Energy consumption is increasing around the world which focuses towards a need to find sustainable energy solutions. Demands for cooling is one of the reason of increasing energy demands. This study focuses on one of the sustainable way to decrease the energy demand for cooling which is solar adsorption refrigeration system. Silica gel-water as the adsorbent-adsorbate pair is used. Flate plate collector is used for hot water generation of up to 80 ˚C. The calculated theoretical COP was found to be 1.16, while the maximum experimental cycle COP and solar COP achieved were 0.152 and 0.076 respectively.**

Keywords— **Energy, Adsorption, Refrigeration, COP, Adsorbent-Adsorbate pair.**

I. INTRODUCTION

"World marketed energy consumption is projected to increase by 44% from 2006 to 2030" according to the U.S. Energy Information Administration [1]. With the increasing trend in energy consumption and worldwide economic growth, the general trend in cooling and air conditioning requirements of industry and buildings is also increasing. To meet the demand in cooling, mechanical vapour compression systems are commonly used which can be classified as conventional systems. These systems are very popular due to their high coefficients of performance, small sizes and low weights. However, they also exhibit some disadvantages such as contributing to global warming and ozone layer depletion and high energy consumptions [2].

Refrigeration is defined as any process of heat removal. More specifically, Refrigeration is defined as the branch of science that deals with the process of reducing and maintaining the temperature of a space or material below the temperature of the surroundings.

To accomplish this, heat must be removed from the body being refrigerated and transferred to another body whose temperature is below that of the refrigerated body. Since the heat removed from the refrigerated body is transferred to another body, it is evident that refrigerating and heating are actually opposite ends of the same process. Often only, the desired result distinguishes one from the other. Therefore, solar energy may be used for cooling. This is usually done by using absorption or adsorption system refrigeration. These systems require a heat source. The heat is used to drive the refrigerant out of another substance which has the opportunity to release it when they are heated and to adsorb it when be cooled. The sun can supply the heat required to operate adsorption or absorption cycles.

A. Principle of Adsorption

Adsorption is a solid sorption process where the binding forces between fluid molecules and the solid medium come from an electrostatic origin or from dispersion - repulsion forces (Van der Waals forces). It is an exothermic process due to the gas-liquid phase change. The energy liberated in adsorption is called isosteric heat, and it depends on the nature of the adsorbent - adsorbate pair.

B. Adsorption Refrigeration Cycle

An adsorption, also called a solid sorption cycle, is a preferential partitioning of substances from a gaseous or liquid phase onto a surface of a solid substrate. This process involves the separation of a substance from one phase to accumulate or concentrate on a surface of another substance. An adsorbing phase is called an 'adsorbent'. Material, which is accumulated, concentrated or adsorbed in another surface, is called an 'adsorbate'. The sticking process should not change any macroscopic form of the adsorbent except the changing in adsorbent's mass [3].

Both adsorption and absorption can be expressed in term of sorption process. The adsorption process is caused by the Van der Vaals force between adsorbate and atoms or molecules at the adsorbent surface. The adsorbent is characterized by the surface and porosity. In the adsorption refrigeration cycle, refrigerant vapour is not compressed to a higher temperature and pressure by the compressor but it is adsorbed by a solid with a very high microscopic porosity. This process requires only thermal energy, no mechanical energy requirement. The principles of the adsorption process provide two main processes, adsorption or refrigeration and desorption or regeneration as shown in figure 1. In case of zeolite and water, as an example, the refrigerant (water) is vaporized by, the heat from cooling space and the generator (absorbent tank) is cooled by ambient air. The vapour from the cooling space is led to the generator tank and absorbed by adsorbent (zeolite). The rest of the water is cooled or frozen. In the regeneration process, the zeolite is heated at a high temperature until the water vapour in the zeolite is desorbed out, goes back and condenses in the water tank, which is now acting as the condenser. For a discontinuous process, desorption process can be operated during daytime by solar energy, and the adsorption or the refrigeration process can be operated during night-time. The solar energy can be integrated with a generator. The single adsorber is required for a basic cycle. The number of adsorbers can be increased to enhance the efficiency, which depends on the cycle. This process can also be adapted to the continuous process.

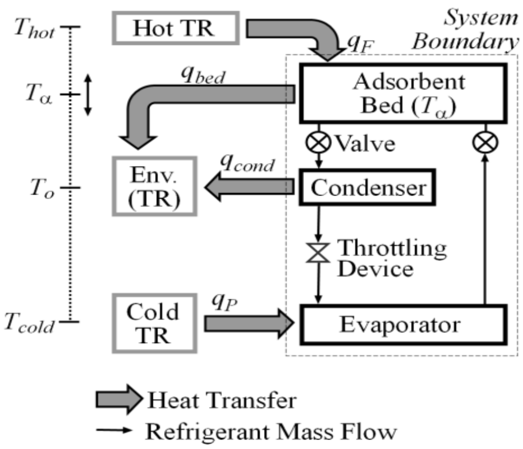

Fig. 1 Schematic diagram for an ideal simple adsorption cycle. [4]

C. Selection of Adsorbent-Adsorbate Pair

At present, three types of working adsorbate and adsorbent, respectively, are favoured for pairing for use in solid adsorption solar refrigeration technology: Ammonia, Methanol and Water for adsorbate and activated carbon, silica gel and zeolite for the adsorbent. The selection of any pair of adsorbent/adsorbate depends on certain desirable characteristics of their constituents, including the affinity for each other. These characteristics range from their thermodynamic and chemical properties to their physical properties and even to their costs or availability.

For refrigerating applications, "the adsorbent must have high adsorptive capacity at ambient temperature and low pressures and a small capacity of adsorption at high temperatures and pressures". The cooling effect, or the temperature attained in the evaporator, depends on the adsorptive capacity at small pressures. This is the property that allows the adsorbent, at a given temperature, to retain vapours from a fluid at a lower temperature. On the other hand, the more intense this property is, the higher the adsorbent regenerating temperature is. Thus we can summarize the considerations influencing the choice of a suitable adsorbent as follows:

In the present work, silica gel – water as adsorbent – adsorbate pair is selected in the solar assisted adsorption chiller. Most of the adsorbent mentioned in the Table 1.2 require medium and/or high temperature heat sources to act as the driving sources. However, silica gel–water and active carbon–methanol adsorption cycles have a distinct advantage over other systems in their ability to be driven by heat of relatively low, near-ambient temperatures, so that waste heat below 100°C can be recovered, which is highly desirable. In this study, silica gel–water has been chosen as the adsorbent–refrigerant pair because the regeneration temperature of silica gel is lower than that of active carbon; and water has a large latent heat of vaporization [5]. Water is non-toxic, non-flammable, non-polluting, stable and free of cost. However, its vapour pressure is very low. It is required to control operating of evaporator above the freezing point. Silica gel is also non- toxic in nature.

II. EXPERIMENTAL SETUP AND DETAILS

The schemetic diagram of solar assisted adsorption water chiller is ahown in figure 2. It consist of evaporator coil enclosed within chiller tank, air cooled condenser, adsorption bed and pressure reduction valve. The position of vacuum gauges, temperature gauges and ball valves are shown in schemetic diagram. The flow diraction is also shown in figure 2.

Just like a conventional compression chiller, an adsorption chiller uses a cycle where a refrigerant condenses at high pressure and temperature and evaporates at low pressure and temperature. However, this cycle is not driven by a mechanical compressor but by a thermal compressor, based on the sorption reaction of silica gel and water, using heat as driving force. Dry silica gel (a porous, glass-like solid) attracts and adsorbs water vapour, until it is saturated. Then it needs to be regenerated; heating the silica gel releases the water vapour at a pressure that allows it to condense at ambient temperatures. Then the cycle of adsorption and desorption can be repeated. The actual experimental setup is showon in figure 3.

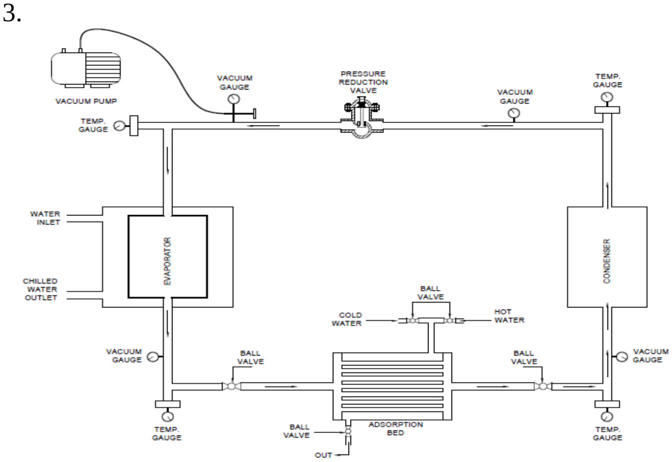

Fig. 2 Schemetic diagram of experimental setup of solar assisted adsorption water chiller

Fig. 3 Experimental setup of solar assisted adsorption water chiller

A. Summary of Design Data of Solar Assisted Adsorption Water Chiller

In designing of the solar powered adsorption chiller some of the assumptions made are here:

Cooling Capacity = 1 KW
Adsorption process time t_{ads} = 10 minutes
Desorption process time t_{des} = 8 minutes
Condenser temperature T_c = 50 ˚C
Evaporator temperature T_e = 15 ˚C
Hot water inlet temperature $T_{H,i}$ = 70 ˚C
Cold water inlet temperature $T_{C,i}$ = 34 ˚C
Chilled water inlet temperature $T_{ch,i}$ = 33 ˚C
Mass flow rate of air $\dot{m}_a$ = 0.15 kg/s
Specific heat of air C_a = 1.005 KJ/kg K
Inlet air temperature $T_{a,i}$ = 40 ˚C
Adsorbent = Silica gel Type A
The properties of silica gel Type A:
Density = 2200 kg/m^3 Specific heat = 0.92 KJ/kg K
Heat of adsorption and desorption h_{ads} & h_{des}= 2500 KJ/kg
Refrigerant = water
Specific heat of refrigerant C_r = 4.186 KJ/kg K

B. Performance Parameters

It is always desirable to study performance parameters related to the solar assisted adsorption water chiller. The most important performance parameters used for the current study are cycle coefficient of performance, specific cooling power, and solar cooling coefficient of performance.

Cycle Coefficient of Performance (COP): Cycle coefficient of performance is defined as the ratio of cooling effect to the net energy required for desired cooling effect:

$$\text{Cycle COP} = \frac{\text{Cooling effect}}{\text{Net energy input}} = \frac{Q_e}{Q_T}$$

The net energy input is given by:

$$Q_T = [\dot{m}_h c_{ph}(T_{hi} - T_{ho})] - [\dot{m}_c c_{pc}(T_{ci} - T_{co})] \quad \text{kW}$$

Cooling effect is calculated as:

$$Q_e = m_w \times c_{pw} \times (T_{ch_i} - T_{ch_o}) \quad \text{KJ}$$

$$Q_e = \frac{m_w \times c_{pw} \times (T_{ch_i} - T_{ch_o})}{\Delta t_{total,cycle}} \quad \text{kW}$$

Specific Cooling Power (SCP): Specific cooling power indicates the size of the system as it measures the cooling output per unit mass of adsorbent per unit time. Higher SCP values indicate the compactness of the system:

$$SCP = \frac{\text{Cooling effect}}{\text{Cycle time per unit of adsorbent mass}} = \frac{Q_e}{m_{ad} \times \Delta t_{total,cycle}}$$

The value of specific cooling power is obtained in ($\frac{W}{K_g}$) unit.

Solar Coefficient of Performance (COP): Since the system is solar-powered, the solar coefficient of performance is also to be defined. This is defined as the ratio of cooling effect to the net solar energy input.

$$\text{Solar COP} = \frac{Q_e}{Q_s} = \frac{Q_e}{Q_T} \times \frac{Q_T}{Q_s}$$

Flat plate collector efficiency ($\frac{Q_T}{Q_s}$) is considered as 50 % according to Duffy & Beckman [6].

$$\text{Solar COP} = \frac{Q_e}{Q_s} = 0.5 \times \frac{Q_e}{Q_T} = 0.5 \times \text{Cycle COP}$$

III. RESULTS AND DISCUSION

A. Results

The hot water temperature is providing driving force to run the cycle. It is essential to analyze the effect of hot water temperature on cooling capacity, cycle COP and solar COP.

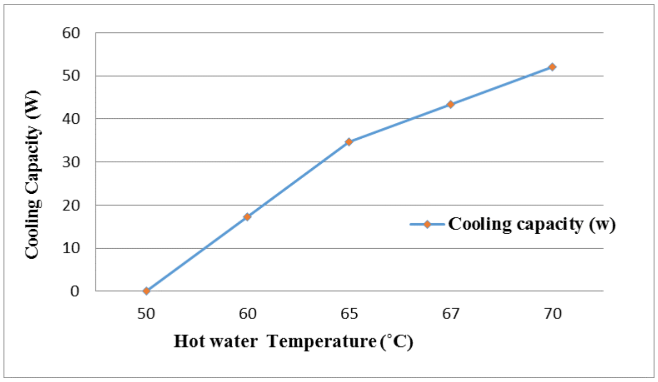

Fig. 4 Hot Water Temperature Influence on Cooling Capacity (W)

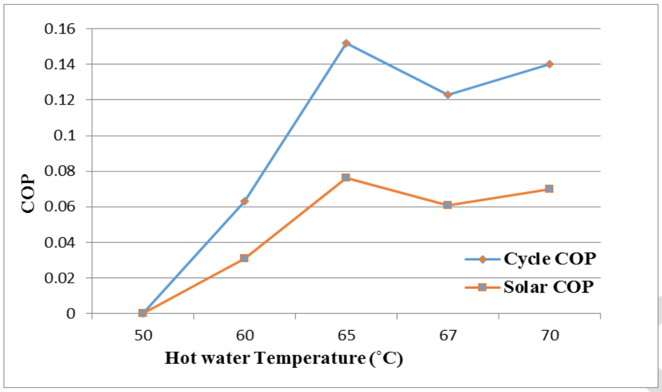

Fig. 5 Hot water temperature influence on cycle COP and solar COP

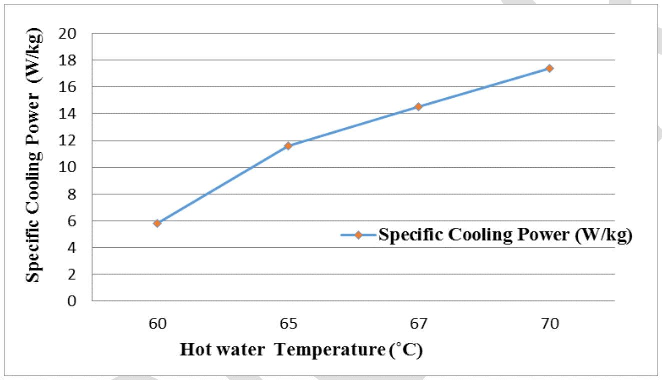

Fig. 6 Hot water temperature influence on specific cooling power

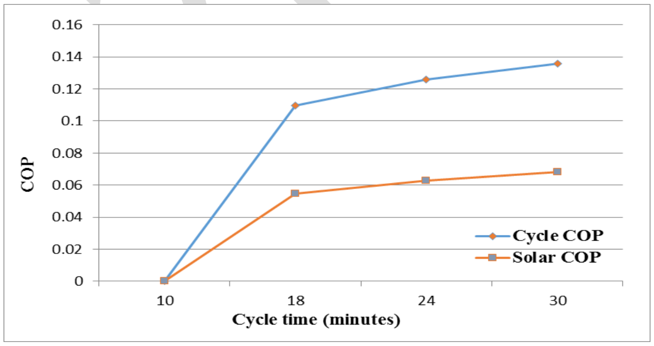

Fig. 7 Cycle time influence on cycle COP and solar COP

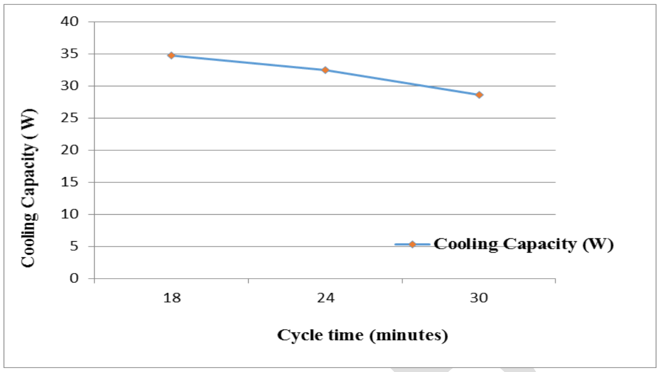

Fig. 8 Cycle time influence on cooling capacity (W)

Figure 4 to 6 shows the variation of cooling capacity, cycle COP, Solar COP and SCP, respectively, with hot water temperature. The cooling capacity and SCP increases with increasing hot water temperature. The variation in solar COP is similar to cycle COP except in magnitude. These variations do not show such linearity. From Figure 7 to 9, it is seen that cycle time has significant effect on cooling capacity, coefficient of performance and specific cooling power. The coefficient of performance increases with cycle time while cooling capacity decreases.

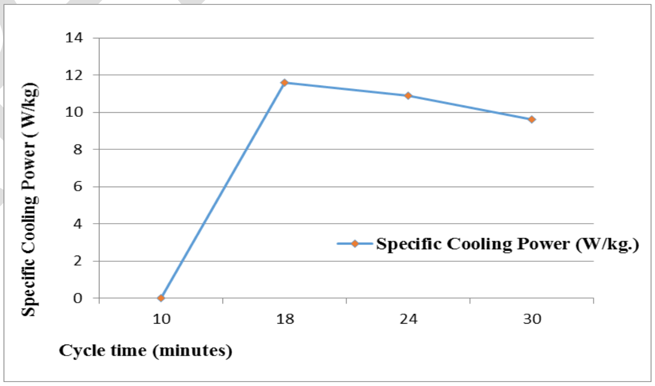

Fig. 9 Cycle time influence on specific cooling power (SCP)

B. Discussion

The hot water temperature drop in adsorption bed is around 6 ˚C to 10 ˚C during each cycle of experiment. The cycle time for desorption (regeneration) was 8 minutes. As hot water pass through adsorption bed, temperature drop was initially high but it reduces continuously during desorption period of cycle. So the values shown in graph are average temperature drop during particular period of cycle. The temperature drop in cold water flowing on adsorption bed was around 3 ˚C to 6 ˚C during each cycle of the experiment. The temperature drop in cold water flowing on heat exchanger of bed was initially high and it decreases during adsorption period of 10 minutes. So the average value of cold water temperature was taken during experiment.

The mass flow of hot water and cold water were 0.032 kg/s and 0.048 kg/s, respectively during the experiment. The chilled water was stored in water storage tank. There were no significant changes in the cooling capacity of system by changing the mass flow rate of cycle. The vacuum obtained in the experimental setup was lower than the designed vacuum required. This may be the reason for not getting any changes in the cooling capacity by varying the mass flow rate. The temperature drop in chilled water storage tank was upto 6 ˚C during the experiments. The influence of hot water temperature on cooling capacity and SCP of system are shown in figure 4 and 6, respectively. It shows that with increasing hot water temperature, cooling capacity and SCP of system increases continuously. These results are quite in tune with the experiment carried out by W. Wang et al [7].There was no cooling effect produced at around 55 ˚C. The maximum cooling capacity of 52.1 W and SCP of 17.4 W/kg were achieved at around 70 ˚C hot water temperature and 18 minutes of cycle time. The hot water temperature produce is provide more heat to adsorption bed which produce more driving force of vapour adsorbate and more amount of adsorbate circulate in cycle. Hence ultimately cooling capacity and SCP increases with increases in hot water temperature.

The influence of hot water temperature on cycle COP and solar COP are shown in figure 5. It shows that both COP also increases with increasing hot water temperature upto some point. But after that both COP decreases with increasing hot water temperature. This is analogues to results obtained by W.Wang et al [7] in their study wherein value of COP decreases with hot water temperature after certain temperature. With increasing hot water temperature heat input to the system also increases as compared to cooling load. This is one of the reasons for decrease in the COP of system. The maximum cycle COP and solar COP are 0.152 and 0.076, respectively, at hot water temperature of 65˚C and cycle time of 18 minutes. It is clear that the average value of solar COP is very much less than the cycle coefficient of performance (COP). Solar COP is the parameter that is defined by considering the performance of solar collector. Solar COP is calculated by multiplying the cycle COP with efficiency of solar collector. The maximum energy absorbed by the absorber plate of collector is only some portion of solar irradiation falling on collector. The remaining heat is lost due to convection and radiation in the solar collector.

Figures 7 to 9 shows the curves of cycle COP, Cooling capacity and SCP respectively, Vs cycle time based on experimental results. From the figures it can be seen that as the cycle time is increased, cycle COP and solar COP are increased and cooling capacities are reduced. The results obtained are quite similar to the results of cooling capacity & COP vs. cycle time by R. de Boer and E.J Bakker [8]. Moreover, according to this figures, in fixed equipment and certain testing condition, the values of cycle time for the maximum COP do not correspond to that of maximum cooling capacity. Actually, the maximum COP takes place when the cycle time is long enough so that heat dissipation in the system approaches zero. However, reasonable experimental data for maximum COP would be confined in a certain cycle time. The maximum cycle COP and solar COP obtained, at cycle time of 30 minutes, are 0.136 and 0.068, respectively. While the maximum cooling capacity and SCP obtained, at cycle time of 18 minutes, are 34.7 W and 11.6 W/kg, respectively.

Obviously, the process of cooling production relates closely to the process of adsorption during cycle, so the process is dominated by the rate of adsorption. In a normal working situation, at the beginning of adsorption, although the amount of adsorbate in adsorbent is lower, the adsorption temperature is higher, thus its adsorption speed does not reach its maximum, so the increase in cooling capacity is gradual. At the end of adsorption, if the cycle time is long enough, the low capacity of adsorption of adsorbent makes refrigeration capacity much lower. Therefore, if the cycle time was too short, then process of adsorption or desorption was terminated before its best capacity was reached, and the performance of the cycle would be worse. Inversely, if the cycle time is too long, cooling capacity in a cycle would not be satisfied because the average speed of conveyed adsorbate is too low at the end of adsorption or desorption. In a normal working range with shorter cycle time, both COP are low and cooling capacity is high.

IV. CONCLUSIONS

There is an increasing need for energy efficiency and so thermally driven adsorption systems in many world regions are essential. Regions with a warm climate and no steady electricity supply are the most potential regions for adsorption chiller. The main advantage of the solar adsorption chiller is its ability to utilize low temperature solar/waste heat as the driving heat source in combination with a coolant at 30°C. Flat plate solar collectors in any tropical climate can effectively produce the required driving energy for the chiller making it superior to any other commercially existing cooling technology.

Solar assisted adsorption refrigeration system is a viable solar cooling technology. Flat plate collector solar water heater system is well suited for supplying hot water up to 80 ˚C during experiment at collector efficiency of 50 %. Silica gel-water as adsorbent-adsorbate pair is well suited for the solar assisted adsorption water chiller, whenever source of heat is available at and below 100˚C. The cooling capacity and COP of adsorption refrigeration system is strongly influenced by the heat source temperature and cycle time. The calculated theoretical COP of solar adsorption chiller is found to be 1.16 with heat source temperature of 80 ˚C. In experimental study, the maximum cooling capacity and SCP achieved are 52 W and 17.4 W/kg, respectively at hot water temperature of 70˚ C and cycle time of 18 minutes. The maximum cycle COP and solar COP of adsorption chiller obtained during the course of this work, are 0.152 and 0.076, respectively. The hot water temperature in the range of 65˚C to 67˚C and cycle time in the range of 18 minutes to 24 minutes emerges as the optimal operating parameters to achieve optimal performance in terms of cooling capacity, specific cooling power, cycle COP and solar COP.

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