Review of the Adsorption Cooling Technology and Design of an Adsorber Bed Heat Exchanger

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Abstract- Adsorption cooling technology gained attention of researchers as soon as Montreal protocols adopted in 1987 and Kyoto protocols in 1997. Adsorption refrigeration system do not increase global warming as well as it has zero Ozone depletion potential. The interesting thing about this system is that; it can be powered by low grade energy and uses natural refrigerant. In this way, no protocols could be violated. This 'Green technology' evolved as an emerging technology in various applications involving air conditioning. This technology is the best suitable option for existing harmful cooling technologies. This cooling system works on the Adsorption principle. Compressor of vapour compression refrigeration system is replaced by adsorber bed. Adsorber bed is filled with adsorbents which has micro-pores on the surface. Refrigerant molecules; well known as Adsorbate, adheres to adsorbents. The design of adsorber bed heat exchangers needs to be taken care of in such a way that, the heat and mass transfer rate should be as high as possible. This paper presents a review of different types of adsorber bed, variety of adsorbents and the adsorbate. This paper focuses on the selection of adsorbents and adsorbate pair according to temperature of hot and cold source, further advancements required to be done in future to make the technology compatible with the present technologies to achieve an objective of pollution free cooling technology.

Keywords – Adsorption, Adsorbent, Adsorbate, Adsorber bed heat exchanger.

I. Introduction

According to the report of the International Institute of Refrigeration, located in Paris, approximately 15% electrical energy utilized for refrigeration and air conditioning applications. Amongst this energy 45% energy is used for air conditioning of commercial and household purposes alone. A lot of electrical energy, consumed by Conventional vapour compression refrigeration machines leading to depletion of fossil fuel resources also refrigerants used in the systems are responsible for emission of the Green house gases. Constitutes present in the refrigerants, are CFCs and HCFCs, causes depletion of ozone layer present in the stratosphere [1]. Refrigeration and air conditioning processes evolved continuously according to ecology. CFC's and HCFC's use has been restricted after Montreal (1987) protocols were accepted. After that refrigeration systems continue using HFC's,because it has zero Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), but it also lead to increase emission of greenhouse gases which has been taken care in Kyoto (1997) protocols. This was the basic reason that researchers were searching for alternative technology. Adsorption refrigeration technology is the system which uses environmentally friendly refrigerants, operates on low grade energy like solar energy and residual heat content of many thermal processes, consumes negligible amount of electricity when compared with Vapour compression refrigeration system [2].

Consider a situation of idling in vehicles. Idling can be defined as the running of an engine when vwhicle is not moving. During this period tremendous amount of thermal energy is consumed by vehicle. This implies that, GHG (Green House Gases) will be released in large amount in the atmosphere. Same situation is valid for long hauling trucks where engine consumes rich mixture of air and fuel [3]. ADCS is most suitable solution over this type of situations in vehicles where excess thermal energy or exhaust heat can be effectively utilized for regeneration of adsorber bed. Bagheri et al. [3] developed an Anti-idling Air-conditioning system to study the heat transfer characteristics. Mathematical and experimental model shows that ADCS can be effectively powered by exhaust heat or excess heat of idling or hauling vehicles for any cooling load. Yongfong Zhong et al. [4] developed an ADCS for air-conditioning of Heavy duty trucks. This system is a newly implemented technology to reduce truck idling which is powered by engine waste heat when the engine of a truck is running, and operated by fuel fired heaters,when the engine is off. Verde et al. [5] also developed an ADCS for air-conditioning of truck cabin which is driven by waste heat available at the exhaust of an engine. This is kind of a global innovative dynamic model which meets effectively its cooling load and it has been concluded that system can able to provide sufficient amount of cooling for such cooling requirement. ADCS system seems to be bulky for passenger cars and light duty trucks. On the other hand Jiangzhou et al. [6] developed an ADCS for air-conditioning of cabin of locomotive driver cabin. This system meets demands of operating conditions and environment conditions effectively so that driver of locomotive do not feel uncomfortable in the torrid environment. This prototype machine was installed for one year in the DF-4B No.2369 locomotive in China. Zhong et al. [7] developed an ADCS for passenger cars and light-duty trucks and tried to reduce its size.this System is also powered by exhaust heat so that fuel economy improves. It is necessary to reduce the size of the system in order to accept ADCS system commercially in light duty vehicles and passenger cars. This could be the need for research in the field of Adsorption cooling technology. Along with this Adsorption cooling technology facing a problem of low COP and SCP because of low heat and mass transfer rates. In the upcoming years innovative research is invited which can contribute to the efforts taken to solve these type of problems.

This paper reviews the ADCS for different application and mainly focuses on the type of hot source, which can be used for regeneration of an adsorber bed. According to Asian climatic conditions, Solar energy and Exhaust heat available at the outlet of an engine or residual heat content in the radiator can be effectively used as a hot source to drive ADCS. Further, it focuses on the design of an Adsorber bed and modifications done in the design to improve heat and mass transfer rates so that SCP of system boosted.

II. ADSORPTION COOLING SYSTEM (ADCS)

i. *Principles of adsorption*

Generally, sorption technology consists of open and closed refrigeration systems. Open systems well known as humidification and dehumidification processes by using solid or liquid desiccants. Closed system are absorption and adsorption refrigeration systems. Sorption principle involves physical or chemical attraction between the pairs of substances to produce cooling power. Sorption systems have capability of transferring thermal energy into cooling power [8]. Adsorption refrigeration system is of our main concern here. Adsorption cooling technology works on the principle of Adsorption. Process of adherence of adsorbate molecules (liquid or gases) on the porous surface (solid) of adsorbent is known as adsorption. Adsorption process is exothermic process and hence this energy to be extracted out of the system [9].

ii. *Thermodynamic cycle of ADCS*

ADCS consist of adsorber bed (heat exchanger) filled with adsorbents, condenser, expansion valve and evaporator. Arrangement of components is as shown in Fig. 1.

Pressure is increased in the system when the adsorbate molecules continue to build up in the pores of adsorbent due to Van der wall's forces. This thermal compressor replaces the mechanical compressor in the vapor compression refrigeration system [10]. processes can be shown on Clapeyron diagram (ln P versus -1/T) as shown in fig. 2. A complete cycle can be divided in between two half cycles as 'Heating–Desorption–Condensation' and 'Cooling-Adsorption–Evaporation'.

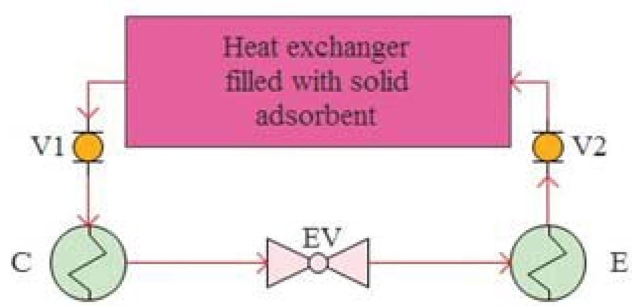

Fig. 1 – Arrangement of ADCS: *C = Condenser, E = Evaporator, V1 and V2 = Valves, EV = Expansion valve* [9].

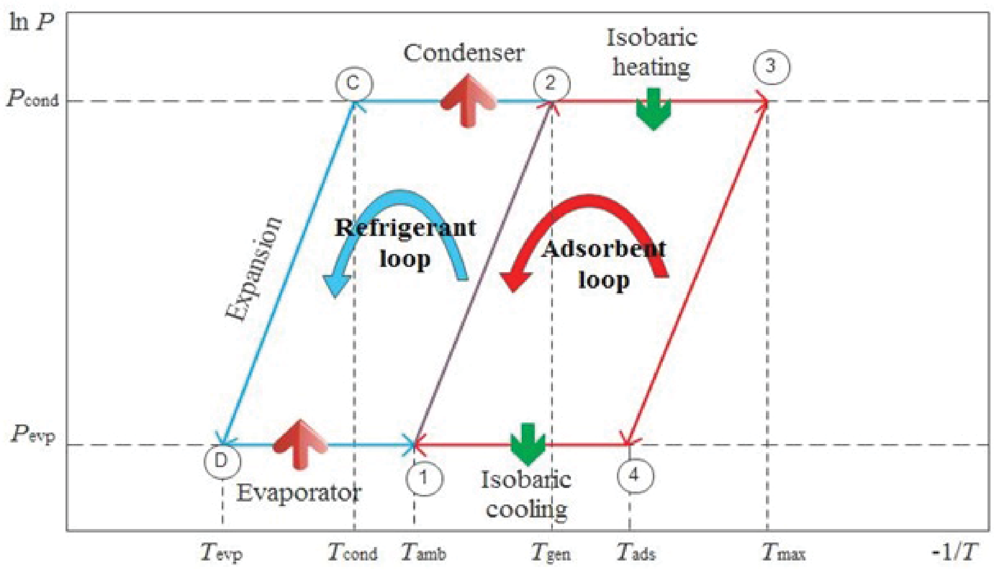

Fig. 2 - Clapeyron diagram for the basic single bed Physisorption thermodynamic cycle: 1-2 = Isosteric heating process, 2-3 = Isobaric heating process, 3-4 = Isosteric cooling process, 4-1 = Isobaric cooling process, 2-C = Condensation process, C-D = Expansion process, D-1 = Evaporation processs [9].

iii. LITERATURE REVIEW OF ADCS USED FOR DIFFERENT APPLICATIONS

Commonly used refrigerants are Silica-gel, Activated carbon and Zeolite. Amongst them Silica-gel and zeolite has been widely used because of having low regeneration temperature (below 85 ºC) and long life. Silica-gel is most suitable for vehicle cooling applications, because it can be regenerated using hot water coming out of the radiator [11]. Also, silica-gel is the prime choice where solar energy is to be used for regeneration of bed [10].

Wang et al. [12] verified adsorption deterioration of silica-gel/Water pair in ADCS. From experimental results, it has been concluded that the water uptake capacity of silica-gel decreases around 45%, when Solid particulates blocks the micropores present in silica-gel. Adsorption capacity decreases due to higher frequencies of adsorption and desorption. Adsorption capacity of silica-gel can be restored back after soaking in the acid solution and washed by the distilled water. Chang et al. [13] developed a two-bed silica-gel/water ADCS with tube and plate fin type heat exchangers as shown in Fig. 3. A solar operated system, both for heating and cooling was designed in a golf course of Taiwan and field test conducted. A cooling power of 9 kW and a COP of 0.37 obtained for operating conditions of 80 ºC hot source, 30 ºC condenser cooling water , and 14 ºC chilled water inlet temperatures. SCP of 72 W/kg of adsorbent has been achieved.

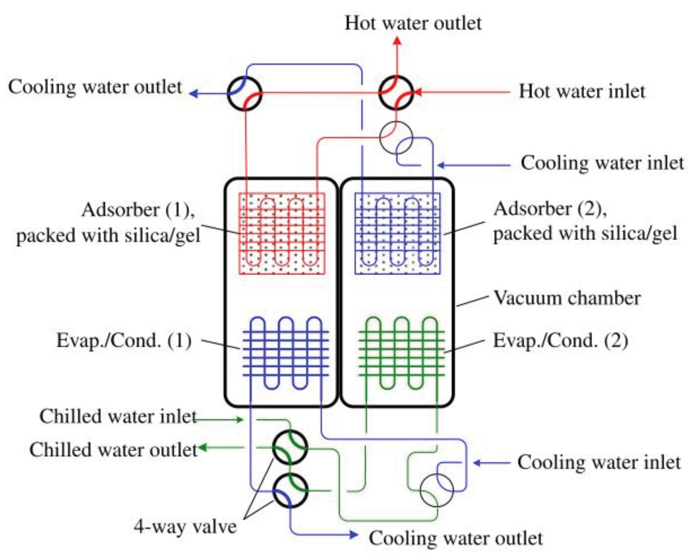

Fig. 3 – Schematic arrangement of ADCS developed by Chang et al. [13]

Chen et al. [14] designed model of ADCS without vacuum valves to improve the reliability. The system made of two different chambers consist of separate adsorber bed, condenser and evaporator as shown in Fig. 4. A common chilled water tank is adopted to decrease the variation in chilled water outlet temperature. The operating conditions adopted were, 82 ºC - average hot source temperature, 32 ºC - condenser water inlet temperature, and 12.3 ºC - chilled water outlet temperature. The cooling power and COP were achieved, 9.60 kW and 0.49 respectively.

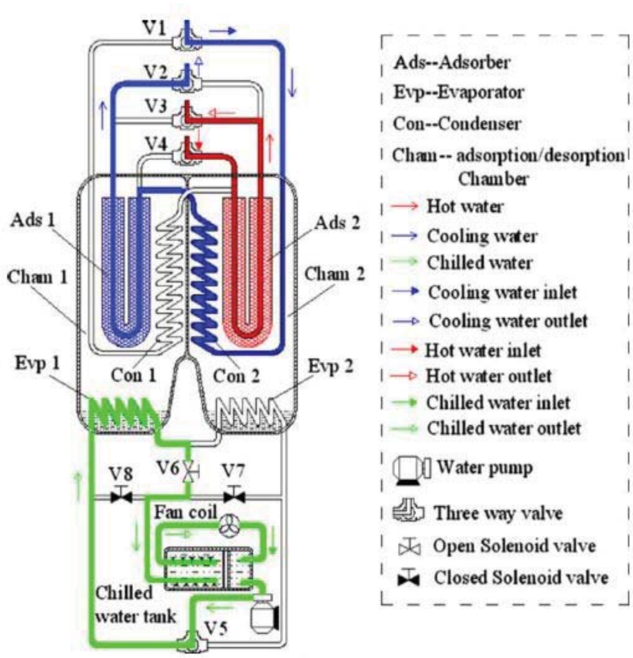

Fig. 4 – Shematic of ADCS designed by Chen et al. [14]

Solar energy has been widely used as a hot source for ADCS. Solar collectors were used to collect an ample amount of solar energy which can not only used for desorption process but also for domestic or industrial purposes. Installation cost of solar operated ADCS is more but operating cost is low [10]. Many large systems were developed and studied by researchers. Zisheng Lu et al. [15] designed novel heat pipe ADCS at the Green building of Dezhou city, China. It is kind of the biggest system designed for building. System consist of 2 adsorber beds, each one filled with 65 kg of microporous silica-gel. This system investigated for operating conditions; 79.0 ºC as the temperature of the hot source, 25.4 ºC as the temperature of cold water used for adsorprtion process and condenser, 13.7 ºC as the temperature of chilled water outlet. The cooling power and COP obtained are approximately 18 kW and 0.65 respectively. The study concludes that the cooling power is directly proportional to the temperature of hot source.

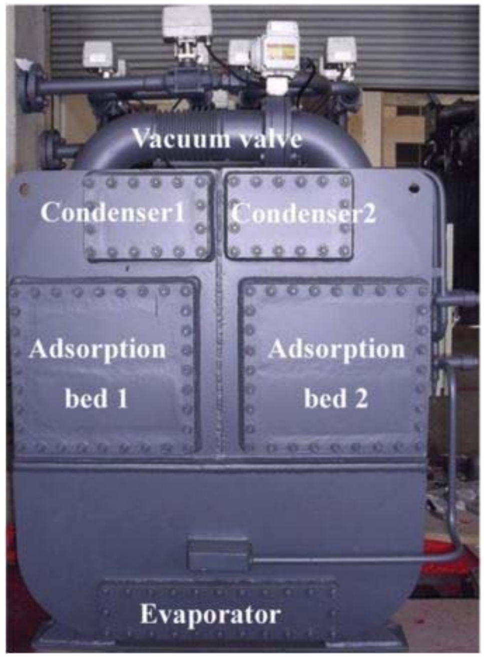

Fig. 5 – pictorial view of adsorption chiller operating at green building, Dezhou city, China.

One more kind of large system designed in Dhaka-23º46´ N (latitude), and 90º23´ E (longitude), Bangladesh by Rifat Ara Rouf et al. [16] as shown in Fig. 6, for investigation purpose of climatic condition, suitability for operation of Adsorption chiller.

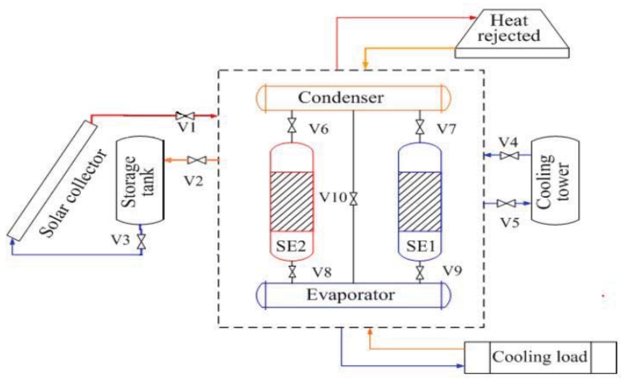

Fig. 6 – Schematic of solar operated ADCS in Dhaka, Bangladesh

The solar unit can be used for dual purpose, not only as a hot source for ADCS but also as a hot water supply source for household purposes. Concerning unit consists of two adsorber beds filled with Silica-gel and water is used as an adsorbate. It has been confirmed that climatic condition of Dhaka requires 30 enhanced CPC (compound parabolic concentrator) collectors of area 2.415 m^2 fitted with a storage tank of hot water have volume 2.197 liters, so that the needs could be fulfilled [16].

Qasem et al. [17] constructed an ice maker based on adsorption principle at Dahran city, Saudi Arabia. This solar driven system consist of adsorber bed filled with activated carbon an an adsorbent and methanol as an adsorbate. System is evaluated experimentally to obatain the value of COP for varying temperature of condensation. According to results obtained, a system can produce more than 5 kg of ice per m^2 of collector area during winter days and around 3 kg during summer days. From this, it is obvious that performance of the system is more in winter than summer days.

On the other hand, song et al. [18] developed an adsorption ice making system to determine the effect of desorption temperature and desorption process time on the performace of the system. Activated carbon (Adsorbent)-Methanol (Adsorbate) pair is used. This solar operated system able to produce 7.7 kg ice daily for 7 hours desorption time which is said as an Optimal time of Desorption. It has been concluded that capacity of ice producing is directly proportional to desorption time. Cycle COP of 0.0322 obtained for daily 5.1 kg ice production when the desorption temperature was maintained at 94 ºC, while no ice production when desoprtion temperature was maintained at 85 ºC and 75 ºC. On the other hand COP and heat utilization factor decreases as desoprtion temperature and time increases. Hence, to decide the optimal desorption time is important so that less amount of heat loss would take place during desorption process.

Zhai et al. [19] developed an ADCS for 'Green Building' of Shanghai Institute of Science. To accomplish the hot source, around 150 m^2 of evacuated tube solar collector array is erected. Two chillers developed each of capacity 8.5 kW. Experimental results show that the average system of both chillers is 0.35 when the system runs continuously for 8 hours. The average cooling capacity of the system was 15.3 kW during an 8 h operation reach maximum value of 20 kW for summer conditions.

III. Design of an Adsorber bed heat exchanger

i. Basic information

Adsorber bed is one kind of heat exchanger filled with adsorbent. Adsorber bed is nothing but the 'Thermal Compressor' of ADCS. Provision is made through bed to incorporate flow of adsorbate. Heat and mass transfer are associated phenomenon with adsorber bed. Our prime focus is to increase heat transfer rate, which can be increased by increasing surface area between the heat transfer fluid and adsorbent material during adsorption and desorption processes. Similarly mass transfer resistance should be minimum between adsorbate and adsorbent particles. Poor design of the adsorber bed leads to the decrease in SCP of system because of low mass transfer rates [20]. Many types of heat exchangers can be used as an adsorber bed and many types of modifications can be done to get the enhanced results [9].

ii. *Literature review of the different types of heat exchangers used as an adsorber bed*

Amir Sharafian et al. [9], studied different types of heat exchanger designs, can be used in ADCS. Comparison between the nine types of heat exchanger types have been done for the SCP, COP, and adsorber bed to adsorbent mass ratio (AAMR). Heat exchanger types as shown in Fig. 7 are, Spiral plate, shell and tube, hair-pin, annulus tube, plate fin, finned tube, plate tube, simple tube, and plate. Amongst all, finned tube heat exchangers have higher heat and mass transfer rate, which makes it most suitable. Finned tube adsorber bed has now become a prime priority of many researchers because of high heat and mass transfer rates and can be boosted by doing modifications.

Amir Sharafian et al. [21] expermimentally studied impact of fin spacing on the distribution of temperature inside the finned tube adsorber bed. When finned tube adsorber bed is to be used for vehicle air conditioning application, it is of prime focus to reduce AAMR (Adsorber bed to Adsorbent Mass Ratio) and temperature gradient. With this aim an interchangeable copper heat exchanger filled with 2-4 mm silica gel bids type ADCS developed to analyze the effect of space between the fins. From the experiments, it is concluded that, as number of fins increases, i.e. fin spacing decreases, then for shorter cycle time, Heat transfer rate increases. After the optimum value of fin spacing, the effect gets reversed.

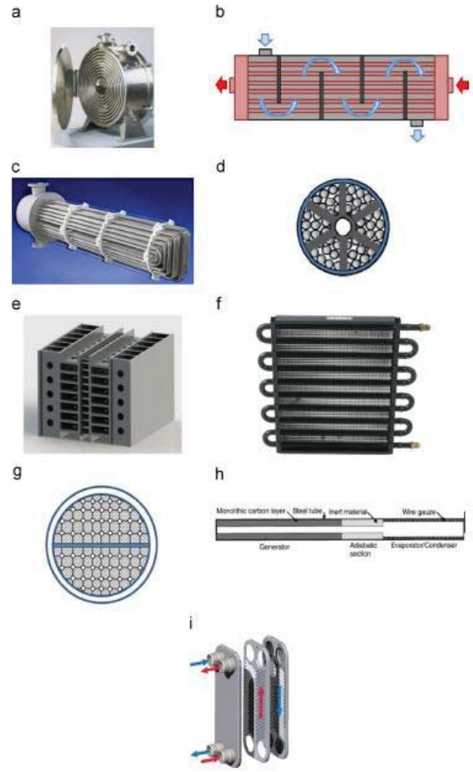

Fig. 7 – different types of heat exchangers used in ADCS. *(a) Spiral plate (b) Shell and tube (c) Hairpin (d) Annulus tube (e) Plate fin (f) Finned tube (g) Plate-tube (h) Simple tube (i) Plate. [9]*

Xu Ji et al. [22] developed, finned tube absorber collector, as shown in Fig. 8, made of an aluminum alloy to increase heat and mass transfer rates. This ice making system powered by solar energy and using Activated carbon/methanol pair. It is observed that, the heat and mass transfer in the collector is directly proportional to the no. of internal fins and the mass transfer channel. Experimental results show maximum COP of 0.122 and maximum daily ice-making capacity around 6.5 kg.

Fig. 8 – finned tube filled with Activated carbon [22].

Restuccia et al. [23] developed a new type of adsorber bed by doing coating of an adsorbent (Zeolite) powder around the tubes of heat exchanger. Care has been taken that the coating material should have good hesive property and good mechanical stability. Voids and empty space between the particles of an adsorbent material decrease, which decreases the mass transfer resistance and large amount of adsorbent material comes in contact with the heat transfer tube which increases heat transfer rate. With this technique, SCP of system increases. Andrea et al. [24] also developed a coated adsorber bed in which SAPO 34 is used as an adsorbent and this material binded around the tube by using Bentonite clay. An optimal thickness of the coating is determined experimentally to study adsorption kinetics.

IV.CONCLUSION

Adsorption cooling technology is the best alternative for vapour compression refrigeration system as it is thermodynamically stable, non-toxic, non flammable and environmentally friendly. Development in ADCS is of prime importance now a days due to restriction on some refrigerants which affects the environment through Ozone layer depletion, Global warming and Emission of Green House Gases (GHG). Adsorbent-Adsorbate pair incorporated in ADCS is environmental friendly, non-toxic, non-corrosive. ADCS has simple controls and easier for maintenance point of view as there are less moving parts. ADCS has been widely used for refrigeration and air-conditioning purposes in large buildings, Locomotive driver cabin, Heavy and light duty cars, passenger and mobile cars, etc. ADCS are of a prime focus where excess amounts of residual heat content are available. However, complete commercialization of ADCS is facing challenges like low SCP and COP. Also, size of Adsorber beds is a major drawback in the way of upgradation of the system. There is a need to increase the thermal conductivity of adsorbent material and mass transfer rate. Amongst the different types of adsorber bed heat exchanger design available, finned tube adsorber heat exchanger is most suitable because of having higher heat transfer area. Coating of adsorbent material around the tubes of heat exchanger reduces the thermal resistance between adsorbent and adsorbate material which was high due to the presence of voids earlier. Modifications in the design of heat exchanger are well accepted as a solution to increase heat utilization in the ADCS. Development in the Adsorption cooling technology is required in future to make the system commercially acceptable.

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