Development Trend of Solar-powered Adsorption Refrigeration Systems: A Review of Technologies, Cycles, Applications, Challenges and Future Research Directions

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***Abstract*— Energy economy, nature conservation and sustainability remain the focal points of the global world. Due to the increase in the global consumption of limited primary energy and the ecological consideration for refrigerants choice, solid desiccant refrigeration systems powered by solar energy, also known as solar adsorption refrigeration systems (SARS) have been the subject of extensive research for cooling applications geared to meet the fast growing refrigeration needs of the rural areas of developing countries. Some merits of SARS include but are not restricted to: low energy intensity, use of low grade heat sources and being eco-friendly thereby meeting the current global regulations. However, these systems have not been able to fully compete with, let alone replacing vapour compression refrigeration system (VCRS) because of some identified bottlenecks. Still with the aim of improving the performance of SARS, some considerable works have been recently carried out that merit an updated review. Therefore, a comprehensive plethora of the development trend in solar adsorption refrigeration (SAR) spanning through its allied technologies, cycles and applications has been extensively presented in this work. The latest published journal papers available through ScienceDirect, open access manuscripts, Google scholar and patent are inclusively reviewed. Evaluation of the relative quantitative and qualitative performances of the technology are also presented. Furthermore, the challenges to its wide deployment and future research directions are likewise presented. This current progress in the technology with its potential of low carbon footprint could provide the required impetus for fast tracking its development and wide application.**

Keywords—development; trend; solar; adsorption; refrigeration; solid desiccant; advanced ; intermittent; cycle

1. INTRODUCTION

Refrigeration has multifarious useful applications in the existence and sustainability of human life most especially in the rural areas of developing countries. The storage of medicines, especially temperature-sensitive ones like vaccinations and the preservation of food products including perishable agricultural products like vegetables, fruits, dairy products, farmed fish, meat etc. all require cooling application. Additionally, transportation of these immunization vaccines requires refrigeration for effectiveness. Hence, the preservation of all these products is very critical to the preservation of health and economy of man because loss of harvest oftentimes has an adverse impact particularly on these rural communities, where small farmers lack access to affordable refrigeration systems. Alternative refrigeration systems like SARS can be used to extend the storage life of these farm products and thereby improve the quality of rural economy and health care.

Therefore, there is a deep engineering interest with the aim of addressing two major issues. Firstly, the ecological consideration for refrigerant choice. Conventional VCRS are energy intensive and require access to reliable source of electrical energy whose generation leads to the depletion of the limited global fossil fuel reserves. Moreover, refrigerants used in these systems, like chloro-fluoro-carbons (CFCs) and hydro-chloro-fluoro-carbons (HCFCs) contribute to greenhouse gas emission thereby depleting the stratospheric ozone layer. Secondly, the greater percentage of the residents of developing countries are in remote locations where the coverage of electrical power grid is sparse or even unavailable at all. Hence, cooling applications in those unreached locations require alternative refrigeration technologies.

Interestingly, solar adsorption refrigeration technology, because of its unique feature that, the requirements/demands for cold are often being naturally balanced by the availability/supply of heat, in addition to its economic and ecological merits, remains the focal point of many researches in meeting the cooling demands of these rural locations of developing countries.

The review findings are recapitulated and the advantages of solar adsorption technology are stated in terms of applicability and thermal performance as follow:

- eco-friendliness;
- ability to be driven by low temperature energy sources and over a large range of heat source temperatures;
- fewer moving parts, hence less complexity and simple working principle;
- absence of crystallization/corrosion problem;
- no frequent maintenance requirements;
- no noise and vibration, hence less sensitive to physical impacts;
- durability.

2. EMERGENCE OF ADSORPTION REFRIGERATION

Adsorption-based refrigeration took its emergence from Faraday's laboratory in 1848. Between 1940 and 1945, a calcium chloride/ammonia adsorption refrigeration system (ARS) driven by steam at 100℃ was applied for food storage application on a train from London to Liverpool, United Kingdom.

Contrastingly from the 1930s, there was a sudden emergence of new technologies such as Freon discovery and the successful development of the totally closed compressor which appreciably improved the efficiency of the conventional VCRS [1]. Consequently, adsorption refrigeration technology was not able to withstand the CFCs systems which were noted for high efficiency. Hence, its development was confined to specific niche applications. The 1970s energy crisis further offered a renewed interest for adsorption refrigeration technological advancement, as it can operate on low-grade heat sources. It was however the colossal increase in environmental pollution and the shortcomings of the CFCs systems which were identified in 1990 as the major causes of the ozonosphere depletion and global warming problems that buoyed up research efforts for alternative refrigeration systems by academics globally.

The first sorption conference held in Paris in the year 1992 favoured this technology to gain more worldwide attention [1]. Since then, this technology and its allied aspects are always being researched by academics and companies globally, with the intention of improving its performance.

3. A SURVEY OF DEVELOPMENT TRENDS

Based on working principle, solid desiccant sorption cycles using adsorption refrigeration principle can be classified basically into intermittent and continuous cycles but going through the transitional development history and global scholarly reports, adsorption refrigeration cycles (ARCs) can be broadly classified as shown in Fig. 1.

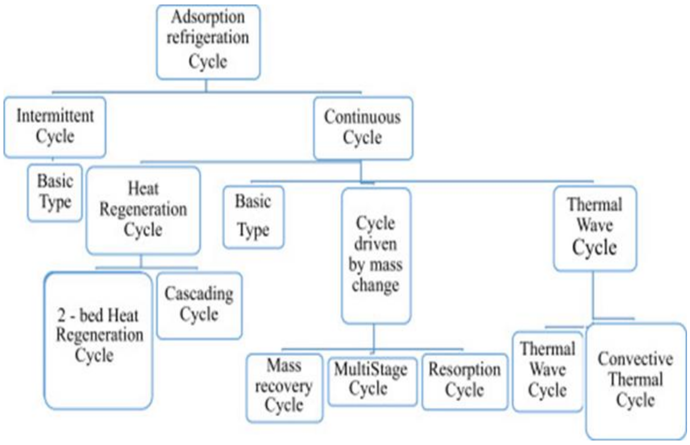

Fig. 1. Classification of adsorption refrigeration cycle based on development history [1]

3.1 Basic or Intermittent cycles

The ancient ARCs, termed the basic cycles, are the simple single-bed intermittent cycles mostly used. This basic cycle has been exhaustively researched when [2] experimented and built a solar-powered ice maker in Orsay. The system, using activated carbon (AC)-methanol pair was able to produce 30–35kg of ice per sunny day at a net solar coefficient of performance (COP) of 0.12.

Reference [3] designed a solar adsorption ice maker with AC-methanol pair for experimental study. The system had the capacity of producing 4 kg of ice per day with a solar COP range of 0.11-0.15.

Reference [4] designed and built a solar-driven refrigerator with a flat plate collector exposed area of 0.92m^2 producing 4-5kg of ice daily at a solar COP of about 0.1 to 0.12.

The results of an experimental study on the dynamic performance of a flat-plate solar ice maker performed by [5] showed that the machine could produce 7–10 kg of ice while receiving 28–30 MJ of radiation energy with a collector area of 1.5 m^2.

Reference [6] developed a refrigerator with a 2 m^2 single glazed solar collector furnished with ventilation dampers to aid night cooling of the adsorbent bed. The system was producing ice of 5 ℃ during day time at a COP ranging between 0.09 and 0.13.

Reference [7] designed, constructed and tested a prototype of a solar-powered adsorption refrigerator of flat plate collector of 1.2 m^2 effective exposed areas with carbon-methanol. The refrigerator yielded evaporator temperatures ranging over 1.0–8.5 from water initially in the temperature range 24–28 ℃ with the maximum daily useful cooling produced being 266.8 kJ/m^2.

A solar powered adsorption refrigerator using AC35-methanol was designed, constructed and tested by [8] and [9]. Experimental results showed that such refrigerator unit could have a solar COP range of 5-8% for an irradiation range of 12,000-27,000 kJ/m^2. With the aim of predicting the performance of this refrigerator and to avoid unnecessary experimental costs, [10] and [11] carried out further studies relating to transient simulation models. The models found to be satisfactorily validated were employed for the optimization of the refrigerator with improvements in the ranges of 29–38% and 26–35% respectively for COP and condensate yield.

The experimental result of the performance analysis carried out by [12] on three thermodynamic cycles (each with a different weather condition) of a solar adsorptive icemaker revealed that with the evaporating temperature of -4.6 ℃, the maximum regenerating temperatures were 100.1, 87.3 and 92.7 ℃, with an ice production of 6.05, 2.10 and 0 kg/m^2 respectively for cycles of clear sky, partially cloudy and overcast nights, with the COP of 0.085.

A solar powered zeolite-water adsorption refrigerator using two compound parabolic collectors (CPC) of total area of 1.029 m^2 having a COP range of 0.838-1.48 was developed by [13].

Reference [14] developed a model of a solar adsorption refrigeration unit powered through a 3.7 m^2 parabolic trough solar collector (PTC) using olive waste-methanol pair. While the solar system COP varied from 0.18 to 0.2, the highest cycle gross COP obtained was 0.75 with a lowest temperature of 4 ℃ in the refrigerated space.

Reference [15] conducted a performance optimization of an AC/methanol intermittent solar adsorption ice maker under Dhahran climate with the MATLAB program. The numerical results show that, with 14.1 kg of AC NORIT RX3-Extra, 5-13 kg of ice per day per m^2 of collector area can be produced with improved solar coefficients of performance (SCOP) of 0.12 and 0.24 in the hot and the cold days, respectively.

A solar powered ARS was designed, constructed and tested by [16]. The system utilized granular 70% CaCl2 + 10% AC + 20% CaSO4/NH3 as a working pair. The refrigerator has an overall COP range of 0.021 - 0.033 with daily ice production range of 0.49–0.63 kg/m^2 .

The experimental result of a laboratory test performed on a built adsorption refrigerator prototype by [17] revealed an evaporator temperature more than 3 ℃, condensing temperature up to 37 ℃ and a COP of about 0.07 under the laboratory working conditions.

A solar ARS with silica gel-water using reflecting surface technique for heat transfer enhancement in adsorbent bed was built and tested by [18]. A minimum evaporator temperature of 5 ℃ and maximum solar COP of 0.09 were achieved.

Based on a set of experimental results obtained with a prototype of a solar adsorption refrigerator using the silica-gel water pair, [19] performed a numerical cum parametric improvement study to improve the overall system performance.

Reference [20] theoretically studied the operating and performance parameters of a solar-driven steady-temperature ARS. Comparative study between different types of AC revealed an optimal COP of 0.73 with 18740.5 kJ as total energy input corresponding to a total daily ice production of 13.65 kg at −3 ℃ for the stone coal based system.

For the purpose of shortened cycle time and improved performance, a novel AC-methanol solar adsorption refrigeration prototype which uses a CPC adsorbent bed was proposed and built by [21]. The experimental results showed that by employing the CPC collectors, the rate of the adsorbent bed temperature increase and the adsorption rate were notably boosted. Hence, the desorption time was reduced by one-third per cycle and consequently, the COP increased by 27% when compared with the conventional adsorption refrigeration systems.

Reference [22] proposed, designed and built a solar ARS with an active enhancing mass transfer method whose novelty is to drop the internal pressure of the system in the desorption process. The experimental results revealed that the maximum COP and maximum ice-making capacity of the system were 0.142 and 7 kg respectively while its average COP showed an improvement of 35.9% as compared with the average COP of the natural mass transfer adsorption refrigeration system with the input radiation energy not less than 14.7 MJ during a refrigeration cycle.

The results of the thermodynamic analysis of a solar powered adsorption cooling cum desalination system carried out by [23] indicates that the hot water inlet temperature, cooling water temperature and condenser temperature have a huge impact on the water production, energy consumption and COP of the system.

Reference [24] conducted a performance evaluation of the prototype of a silica gel-water adsorption based cooling system for mango fruit storage in Sub-Saharan Africa which was developed and set up by Coolar UG, Berlin, Germany. The study showed the cooling cycle time as the most influencing factor for the reduction in storage temperature. It was concluded that the new energy saving storage technology can be adopted for storage of fresh commodities in Sub-Saharan African countries based on its revealed capability of storing fresh mangoes with a 3% mass loss at average inside air temperature of 15 ℃ and relative humidity of 90%.

The numerical simulation and experimental investigation performed on an intermittent adsorption refrigeration cycle (ARC) by [25] resulted in a maximal solar COP of 0.078 and a maximal cooling capacity of 777.96 kJ. The proposed refrigerator also possesses the ability to make the temperature of a 9 kg water-load decrease to 0 ℃ during a partially cloudy day.

A numerical study with commercial computational fluid dynamics (CFD) software was conducted by [26] in order to investigate into the thermal performance of an AC-methanol solar adsorption refrigeration by incorporating finned tube adsorbent bed with a CPC into it. The study showed that the radial heat loss of the finned tube wall was less than the smooth tube and that the temperature gradients of the AC in the smooth and finned tubes during isosteric heating were approximately 28.1 ℃ and 4 ℃ respectively. The authors therefore concluded that the fins had a large effect on the thermal performance of the system.

Based on the study of the solar adsorption cooling systems in the previous years, [27] conducted an experimental study (which was completed in the early autumn of Beijing) on a SAPO-34 zeolite–water solar adsorption refrigeration system (using a PTC) whose bed is modified with built-in fin structure for the purpose of internal heat transfer enhancement. The experimental results showed that, while the system COP ranges from 0.139 to 0.160 for the different cases of fins number, height and thickness, the maximum increase of the specific cooling power (SCP) can be as much as 83.5%. It is then concluded that with more fins applied, the system cycle time could be obviously shortened and hence resulting in a large scale improvement of the SCP index.

Though these basic cycles appear to be simple and reliable, the results of these early works, as recapitulated in Table 1, have signaled some bottlenecks like low COP, low SCP and most especially intermittent refrigeration production. In the quest to mitigate these bottlenecks and thereby improve the efficiency, performance and the practicability of the basic cycles, different advanced adsorption refrigeration cycles are being proposed by various researchers with their performances being studied and analyzed.

3.2 Advanced or continuous cycles

These cycles generally employ the operations of two or more beds to achieve alternate adsorption and desorption processes thereby producing refrigeration continuously. Following is the plethora of the development trend of such cycles:

3.2.1 Heat recovery ARC

This concept was first introduced into the ARS for improving COP based on the principle of recoverer. The heat recoverer used in the adsorption systems is the adsorbent bed itself [28]. According to the corresponding research, heat recovery can improve COP by 25% [29].

Reference [30] used this technique to enhance the COP of his experimental AC-ammonia SARS up to 0.8. References [31] and [32] suggested an improvement by installing more adsorbers into the system. Heat recovery in this process, when compared to the basic cycle, will only be effective if the heat transfer fluid temperature leaving the adsorbers is sufficiently high. Simulation results have shown that the maximum COP value depends on the number of adsorbers and desorbers installed. He later extended the analysis to a system containing six adsorbers and six desorbers at the same temperature conditions and discovered that it is possible to obtain COP as high as 1.16. However, it should be noted that though increased COP could be achieved by adopting multi-beds but at the expense of the system simplicity.

A quasi-continuous ARS with heat recovery whose schematic diagram is depicted in Fig. 2 was experimentally investigated by [33] and [34]. While cooling-adsorption-evaporation is being carried out in adsorber 1, adsorber 2 connected to the condenser is heated to obtain heating-desorption-condensation. The result showed that the system COP was increased by about 25% when compared with one adsorber basic cycle system.

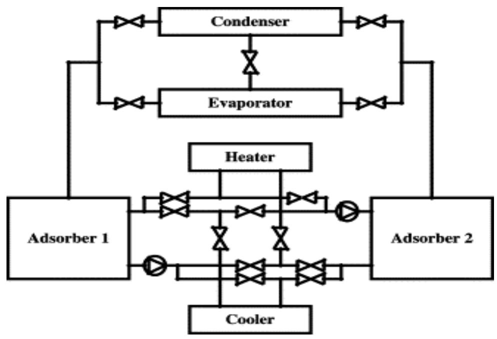

Fig. 2. Schematic diagram of heat recovery two-bed adsorption refrigeration system [33], [34]

3.2.2 Heat and mass recovery ARC

This is one of the most commonly and successfully used cycles in the recent time. Mass recovery is very effective in combining with heat recovery cycle and can raise the system COP by more than 10% [34].

Figs 3(a) and (b) respectively show schematically the principle of the mass recovery cycle and thermodynamic property diagram of heat and mass recovery.

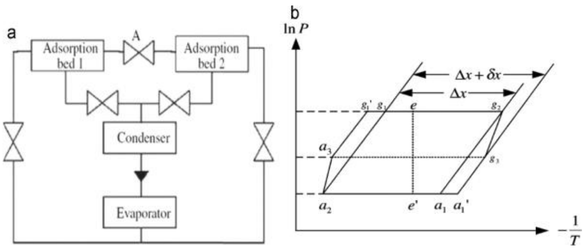

Fig. 3 (a) Principle of mass recovery (b)Diagram of heat and mass recovery cycle [1]

TABLE 1 Summary of solar adsorption systems operating with intermittent cycles

Application	Study Method	Adsorption pair	Collector Area (m^2)	Collector type	Solar radiation	Performance parameters		Reference
						COP	Ice production (kg/day)	
Ice maker	Exp.	AC/Methanol	6	Flat plate	16-19 MJ/day	0.12 net sol	30-35kg/day	[2]
Ice maker	Exp.	AC/Methanol	1.1	-	22 MJ/(m^2.day)	0.11-0.15 sol	4kg/day	[3]
Ice maker	Exp.	AC/Methanol	0.92	Flat plate	17-19 MJ/(m^2.day)	0.1-0.12 sol	4-5kg/day	[4]
Ice maker	Exp.	AC/Methanol	1.5	Flat plate	28-30 MJ/day	0.125-0.14 sys	7-10kg	[5]
Ice maker	Exp.	AC/Methanol	2	Flat plate	19-25MJ/m^2	0.09-0.13 sol	-	[6]
Water cooler	Exp.	AC/Methanol	1.2	Flat plate	559.72 W/m^2	0.007–0.015 sol	-	[7]
Ice maker	Exp.	AC/Methanol	0.72	Flat plate	12-27 MJ/m^2	0.05-0.08 sol	-	[8], [9]
Ice maker	Exp.	AC/Methanol	1.0065	Multi-tubular flat plate with reflector	23.7 MJ/(m^2.day)	0.085 net sol	6.05kg/m^2	[12]
Water cooler	Exp.	Zeolite/Water	1.029	CPC	170 W/m^2	0.838-1.48 sol	-	[13]
Refrigerator/ Cooler	Sim.	Olive waste/Methanol	3.7	PTC	56.2 MJ/m^2	0.18 -0.2 sol	-	[14]
Ice maker	Sim.	AC/Methanol	1	Flat plate +tubes_+ selective coating	-	0.12-0.24 sol	5-13 kg/ (m^2.day)	[15]
Ice maker	Exp.	$CaCl_2$+AC+ CaSO4/ Ammonia	1	Flat plate	13.3 MJ/m^2	0.021-0.033 overall	0.49-0.63kg/ (m^2.day)	[16]
Water cooler	Exp.	Silica gel/Water	-	Flat plate + tubes	10.12 MJ/m^2	0.07 laboratory	-	[17]
Water cooler	Exp.	Silica gel/Water	0.63	Flat plate +tubes+ reflector	19 MJ/m^2	0.083-0.09 sol		[18]
Water cooler	Exp. + Sim.	Silica gel/Water	1	Flat plate	15.12-21.8 MJ	0.056-0.2	Average daily cooling power=225W	[19]
Ice cooler	Sim.	AC/Methanol			18.74 MJ	0.73 sys	13.65kg/day	[20]
Refrigerator	Exp.	AC/Methanol	CR=1.24	CPC	600 W/m^2	0.14 sol	-	[21]
Ice maker	Exp.	AC/Methanol	-	Flat plate + finned tubes	14.7 MJ	0.142	7kg	[22]
Water cooler+ desalinator	Sim.	Silica gel/Water	-	-	-	-	-	[23]
Fruit storage	Exp.	Silica gel/Water	-	-	-	180 litres capacity	Cooling power=19.8 W/120mins CCT	[24]
Ice cooler	Exp. + Sim.	Silica gel/Water	0.36	Flat plate + external reflectors	9.52-9.75 MJ	0.078 sol	0.45 kg Cooling capacity= 777.96 kJ	[25]
Refrigerator	Sim.	AC/Methanol	CR=1.008	CPC	800 W/m^2	-		[26]
Refrigerator	Exp.	SAPO-34 zeolite–water	-	PTC	870–980 W/m^2 3.5-3.6 MJ	0.139-0.160	-	[27]

Sim: simulation; Exp: experiment; sol: Solar; sys: System; CR: concentration ratio; CCT: cooling cycle time

The result of an analytical study done on a two-bed, silica gel-water ARS with mass recovery showed that the cooling capacity of such a cycle is superior to that of conventional cycle and that mass recovery process is more effective for low regenerating temperature [35].

Reference [36] developed a novel silica gel–water ARS noted for its: no refrigerant valves, two adsorbers, two condensers and two evaporators novelty. The experiment results demonstrated that the chiller first prototype had a cooling capacity of 2–7.3 kW with COP of 0.2–0.42 at different evaporating temperatures; while a COP over 0.5 and cooling capacity of 9 kW was achieved at evaporating temperature of 13 ℃ for the second prototype.

This concept was further improved around that same year as [37] and [38] developed a chiller consisting of three vacuum chambers: two adsorption/desorption (or evaporation/condensation) vacuum chambers and one heat pipe working vacuum chamber as the evaporator. With that configuration, the chiller with a COP of 0.38 was able to attain a cooling capacity of 6 kW with 17.6 ℃ chilled water outlet temperature.

A numerical study of a continuous PTC powered-ARS was done by [39]. The study results had put in evidence that the system is capable of a SCP of the order of 104 W/kg, a cooling COP of 0.43, a daily useful cooling of 2515 kJ per 0.8 m^2 of collector area, while its gross solar COP could reach 0.18.

Reference [40] conducted a performance study on a continuous two stage solar hybrid ARS using AC-methanol. The system was producing a cooling effect of 60.75 W and 79.87 W with a mean cycle COP of 0.196 and 0.335 during daytime and night respectively.

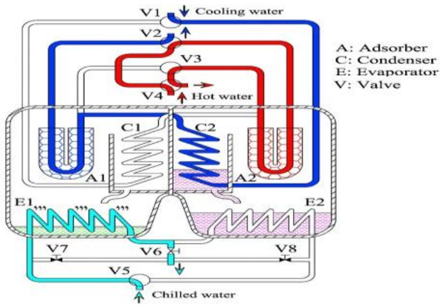

Fig. 4 Schematic of the adsorption refrigeration system with heat and mass recovery processes [41]

Shown in Fig. 4 is a novel heat and mass recovery silica gel-water ARS consisting of a serial heat recovery process between two adsorbers and a mass recovery-like process between two evaporators built by [41]. The experimental results showed that: the optimal ranges of heat and mass recovery time are 25–45 seconds and 5–50 seconds, respectively.

3.2.3 Thermal wave ARC

This concept was first proposed by [42] and [43]. The imperative of designing this was to optimally use exothermic heat in order to reduce the heat required from the external heat source for desorption process and thereby providing efficiency gain [28]. The authors, from their analyses, proved that over 80% of the heat required for desorption process was made available from the bed being cooled without violating the second law of thermodynamics. This could substantially reduce the energy input cost.

Reference [44] investigated the effects of various operating parameters on the performance of an adsorptive thermal wave regenerative heat pump. Though the system was capable of achieving a numerical COP value greater than unity but it was slightly higher for air conditioning purposes as concluded in Spinner's model [45]. However, for efficient running of a thermal wave cycle, large temperature drop and lift are respectively required in the desorber and adsorber. The cycle also needs good bed heat transfer properties which are difficult to get from low thermal conductivity adsorbent materials [46]. Therefore, it can be concluded that thermal wave cycle is better for the system COP but not for SCP [29].

3.2.4 Convective thermal wave ARC

References [47] and [48] in an effort to improve the performance of thermal wave cycle, rather than heating the bed directly as in thermal wave cycle, initiated the heating/cooling of the thermal fluid by packing two inert beds with non-reactive particles. The first half of the proposed convective thermal wave cycle is shown in Fig. 5. With 5 ℃ evaporating temperature, 40 ℃ condensing temperature, 200 ℃ desorption temperature and the heat regeneration rate of 0.8, a theoretical COP of 0.90 was predicted. This system has the advantages of being cost effective as compared to conventional heat exchangers, high COP values and good energy efficiency.

Reference [49] in his interesting effort to enhance the performance of convective thermal wave ARC, proposed a different cycle configuration called periodic reversal forced convective cycle. However, controlling the flow rate of the refrigerant vapour and the high vacuum under which the gas recycle pump works are two technical issues to be solved in order to make the cycle practicable.

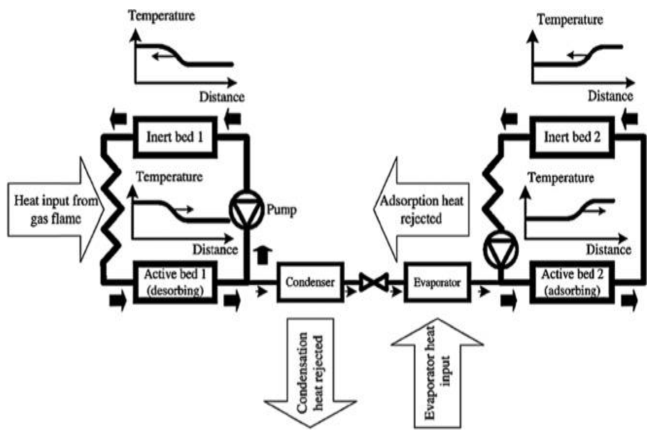

Fig. 5 Adsorption refrigeration system with convective thermal wave cycle [47]

3.2.5 Cascaded ARC

Reference [50] experimented on a cascading adsorptive cycle consisting of two adsorbers: zeolite-water at high temperature stage and an intermittent AC-methanol at low temperature. Experimental cooling COP was found to be 1.06, which was far more than the COP of an intermittent cycle and more than the COP of a two adsorber zeolite water cycle under similar operating conditions. For cascade cycle to be applicable in the practical systems, its reliability and complexity should be studied further [29].

A cascaded mass recovery cycle using multiple mass recovery process (Fig. 6) was proposed and theoretically studied by [51]. Based on silica gel–water adsorption heat pumps, the results show that the COP is superior to that of the basic cycle or conventional mass recovery cycle and that the system can overcome the disadvantages of high complexity and equipment cost which altogether make it more efficient and convenient.

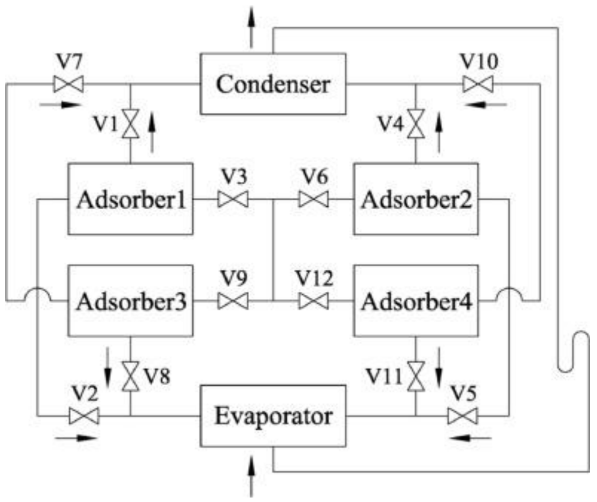

Fig. 6 System configuration of cascaded mass recovery cycle (taking two-stage mass recovery cycle as an example [51]

3.2.6 Multi bed and multi stage ARC

All the cycles discussed above are single stage and so cannot effectively utilize high temperature heat sources and as well do not perform optimally at very low temperatures. The basic concept about this cycle is to perform desorption–condensation and adsorption–evaporation processes at different temperature/pressure levels by using the same working pair [28].

Reference [52] proposed the design and experimental prototype of a two-stage non-regenerative adsorption chiller with silica gel–water pair. With a 55 ℃ driving source in combination with a heat sink at 30 ℃, the chiller's COP was found to be 0.36.

References [53] gave the analytical performance prediction of a continuous multi-bed regenerative adsorption system consisting of 32 simple tubular adsorption modules.

A study was conducted by [54] on combined system consisting of an adsorption–absorption cascading multi-effect refrigeration cycle. The system consists of a high temperature stage of solid adsorption unit with zeolite-water and a low temperature stage of double effect absorption unit with LiBr–water. The working principle of this cycle was demonstrated with Fig. 7. The work showed that the cycle COP can be greatly improved by efficient energy recovery and utilization within the system.

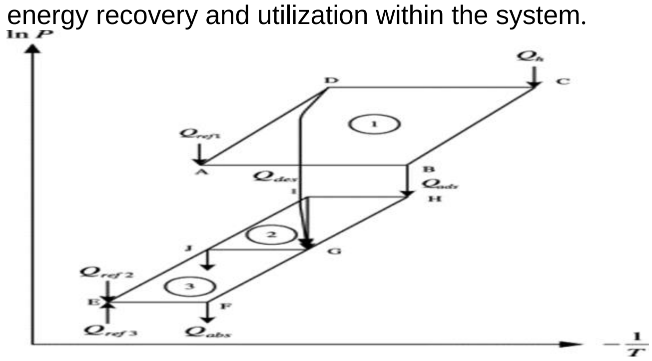

Fig. 7 Adsorption–absorption cascading multi-effect refrigeration cycle: (1) adsorption cycle; (2) high pressure absorption cycle and (3) low pressure absorption cycle [55]

Reference [56] designed a dual-mode, multi-stage, multi-bed silica gel–water adsorption system which can be powered by solar/waste heat of 40-95 ℃. The system is capable of operating in the first mode with the driving source of 60-95 ℃, and in the second mode (whose work is similar to an advanced three-stage adsorption chiller) with the available driving source of 40-60 ℃. The limitation in this operational mode is its poor efficiency in terms of cooling capacity and COP. Simulation results showed that the optimum COP ranges for the three-stage mode are obtained at driving source of 50-55 ℃ and 80-85 ℃ in single-stage mode.

An innovative three-bed adsorption cycle in parallel flow configuration of the heat transfer fluids was proposed by [57]. The simulation result demonstrates that optimum COP values are obtained with 30 ℃ cooling water and driving source temperatures range of 80-90 ℃.

3.2.7 Fluidized bed technology

Reference [58] designed a fluidized-bed adsorber/desorber which can be used in the ARS instead of the conventional fixed-bed. It was concluded that with the new approach, the poor heat and mass transfer in the conventional fixed-bed can be overcome and the system SCP can be appreciably improved with considerably reduced cycle time. The only drawback is that extra electricity is required to run the blower needed for fluidization which makes the technology only suitable for large refrigerating load applications.

3.2.8 Constant temperature Adsorption Refrigeration (CTAR) Cycle

Reference [59] proposed a novel and continuous solar-driven ARS (Figs. 8 and 9), capable of providing cold continuously along the 24hours of the day and whose working principle is based on CTAR cycle.

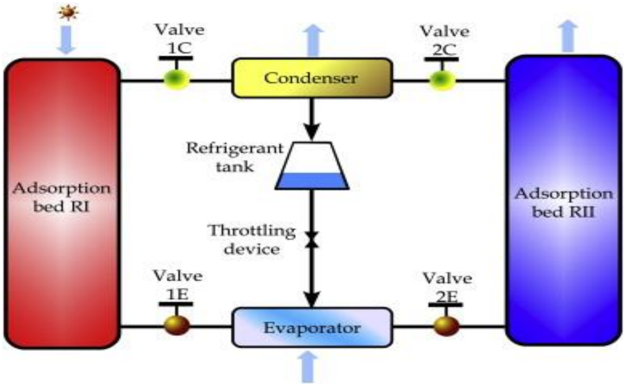

Fig. 8 Schematic diagram of the constant temperature adsorption cooling cycle [59]

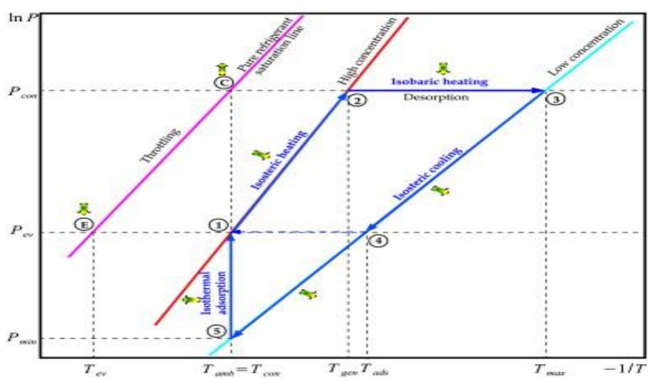

Fig. 9 Clapeyron diagram for the constant temperature adsorption cooling cycle [59]

Reference [60] further applied this principle to their proposed system shown in Fig. 10. An AC–methanol water chiller modelled after the operation of the novel cycle was found to produce a daily mass of 2.63 kg cold water at 0 ℃ from water at 25 ℃ per kg of adsorbent with a cooling COP of 0.66.

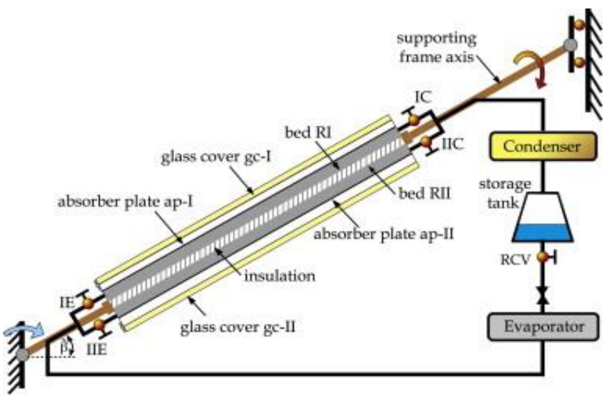

Fig. 10 Schematic diagram of the proposed CO-SAR system [60]

3.2.9 Hybrid systems

Hybrid systems use the basic or intermittent ARC for heat and cold production or in combination with other types of refrigeration systems.

The first hybrid adsorption heating and cooling system was developed by [61]. The system, having zeolite-water pair, was able to achieve space heating and air conditioning purposes.

A hybrid system of solar powered water heater and adsorption ice maker using AC-methanol was proposed and developed by [62]. It was experimentally verified that it is capable of heating 60 kg water to about 90 ℃ as well as producing ice at 10 kg per day with a 2 m^2 solar collector having a COP of 0.144. This was later improved by [63] by including a second tank which served as hot water reservoir.

Reference [64] developed a simulation model of a hybrid heating and cooling solar adsorption system (Fig. 11) capable of reaching a mean heating COP of 0.34 and cooling COP of 0.18 while furnishing 30 kg hot water of 47.8 ℃ .

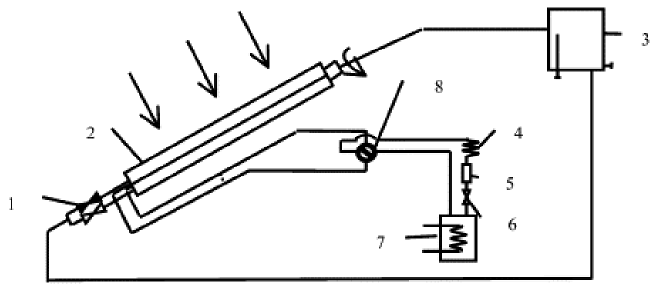

Fig. 11 Schematic representation of Continuous hybrid adsorption refrigeration system [64]

A conventional mechanical compression was supplemented by thermal compression with the aid of a string of adsorption compressors with AC-hydrofluorocarbon 134a pair by [65]. This group realized that almost 40% energy saving is possible by carrying out a portion of the compression in a thermal compressor as compared to when the entire compression is carried out in a single-stage mechanical compressor.

With the intention to utilize low grade thermal energy to drive a refrigeration system that is capable of cooling some critical electronic components, [66] and [67] studied various stages of the laboratory model of a thermally driven adsorption refrigeration unit with three specimens of varying achievable packing densities. It was concluded that packing density of the adsorber plays a major role in the performance of the system.

Reference [68] presented the description and thermodynamic analysis of a hybrid system of solar-powered heater and adsorption ice maker. The simulation results revealed the ability of the system with the COP of 0.62 to heat 50 kg water to about 96 ℃ and also producing 7.2 kg ice per day with a 2 m^2 evacuated vacuum-tube-type solar collector.

Reference [69] recently investigated a polygeneration plant for the production of electric power, cooling and fresh water for a site with a design DNI (direct normal irradiation) of 800 W/m^2 and a 400–600 m^2 solar dish surface. The polygeneration plant shown in Fig. 12 is based on a ©GICE cycle integrated with a ©CryoDesalination process and with a cooling recovery system to make available cooling power at temperatures around 2℃. The study has demonstrated the potential of large solar dish technology used to feed solar energy in an integrated system made of a ©GICE engine, ©CryoDesalination group and a collector of the cold streams for cooling purposes.

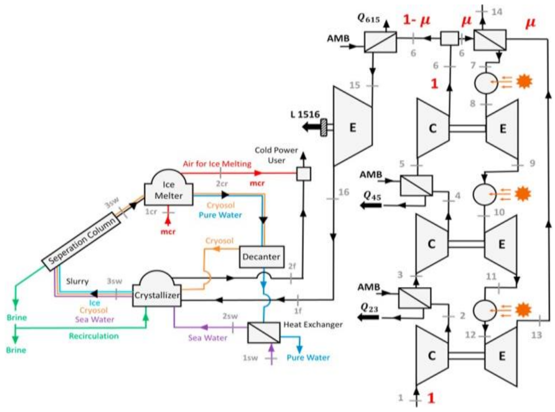

Fig. 12 Polygeneration of power, water and cooling by concentrated solar energy plants equipped with ©GICE engine [69]

3.3.0 Rotary Solid Adsorption Refrigerator

A novel solar powered rotary solid adsorption refrigerator system adopting AC fiber/ethanol (Figs. 13 and 14) was designed by [70] and [71]. The system was said to offer the advantages of higher performance, simple structure, fast and continuous refrigeration, higher thermodynamic coefficient. The authors added that the commercial solar powered refrigerator would be existent in the near future.

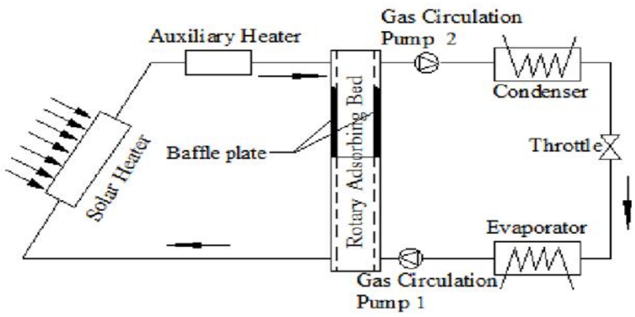

Fig. 13 Operation principle of rotary solid adsorption refrigerator [70], [71]

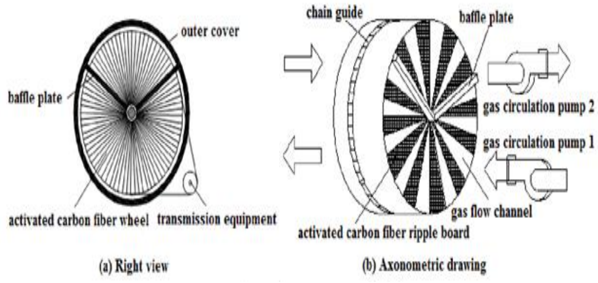

Fig. 14 Rotary activated carbon fibre adsorbing bed [71]

The systems using these advanced cycles are oftentimes very complex and the performance is much low so that these cycles are not used in the practical systems [29].

4. STATE OF DEVELOPMENT

Zeocool (Fig. 15a) is a revolutionary invention developed by Zeotech GmbH [72]. It is a disposable adsorption system with an integrated active zeolite cooling system and separate heating, ideal for shipping or transporting valuable, temperature-sensitive products like medicine, vaccinations etc. around the globe at a constant temperature. This system keeps the payload at a constant temperature between 2 – 8 ℃ for a period of several days irrespective of the outside temperature, which could be -15 ℃ or even +40 ℃. Also developed by this same company is a rugged solar-thermal freezer system (Fig. 15b) that requires less electrical energy than the conventional systems. This system which utilizes zeolite technology for providing icepacks for refrigerated transport has four icepacks in the freezer area and frozen icepacks in the lower storage volume. Zeotech similarly designed a small-scale testing unit for solar thermal cooling and heating utilizing zeolite technology (Fig.15c). It also developed a single effect solar powered cooling and solar heating applications by integrating an innovative zeolite technology in solar-thermal systems using compound parabolic concentrator systems. The integration of the zeolite technology gives the advantage to make use of a heat pump effect, which enhances the coefficient of performance of the overall system.

Shown in Fig. 16a is a commercial solar adsorption icemaker produced by the French company BLM. A Cogeneration system for cooling, heating and power (CCHP) with an adsorption refrigerator shown in Fig. 16b was installed in Maltester Hospital in Kammenz of Germany. The hybrid chiller whose cooling power was 105 kW received heat from fuel cells and solar energy.

Fig. 15 (a) Disposable adsorption cooling box (b) solar-thermal freezer with zeolite technology for providing icepacks for refrigerated transport (c) Small-scale testing unit for solar thermal cooling and heating utilizing zeolite technology [72]

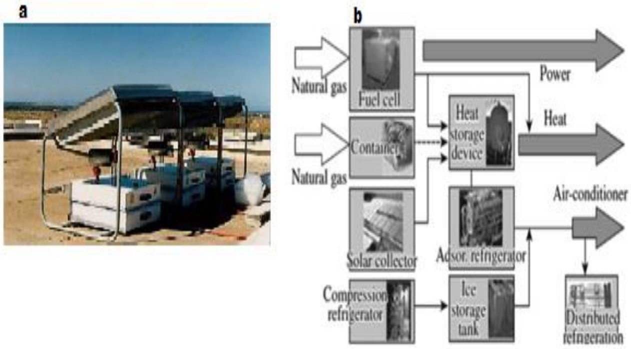

Fig. 16 (a) Photo of BLM solar ice maker (b) CCHP system installed in Malteser hospital [1], [28]

Fig. 17 shows a commercial adsorption chiller successfully manufactured by HIJC Company in Texas, USA [73]. The double bed silica-gel/water chiller which can be driven by a heat source between 50 ℃ and 90 ℃ (like solar source) can produce chilled water of temperature less than 3.3 ℃ .

Fig. 17 Photo of adsorption chiller manufactured by HIJC [73]

MYCOM Company, Japan [74] successfully manufactured a zeolite/water Adsorption chiller Adref-Noa shown in Fig. 18a which can produce 5-15 ℃ chilled water from 60-80 ℃ heat source with a COP of 10. This same company also developed a silica-gel/water adsorption air conditioner (shown in Fig. 18b) which can be driven by 75–95 ℃ heat source while producing 9-14 ℃ chilled water with cycle time in the range 5-7 minutes.

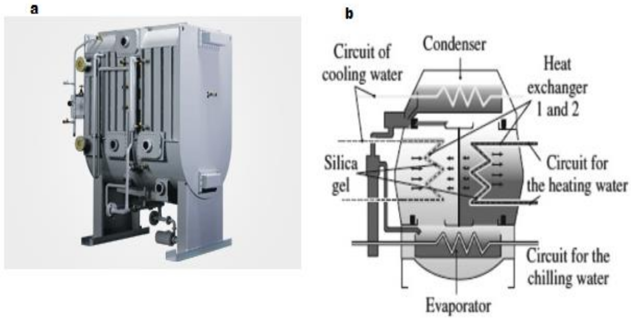

Fig. 18 (a) Figure Photo of AdRef-Noa | Mayekawa chiller [74] (b) Schematic diagram of Makayewa silica-gel/water adsorption chiller [1]

A double bed single stage silica gel/water adsorption chiller with cooling capacity of 12.63 kW was manufactured by Nischiyodo Kuchouki Co. Ltd., Japan. The system was having a COP of 0.4 and operating with a heat source of 85 ℃. Shown in Fig.19 is also a 50-70 kW range Nischiyodo Kuchouki adsorption chiller.

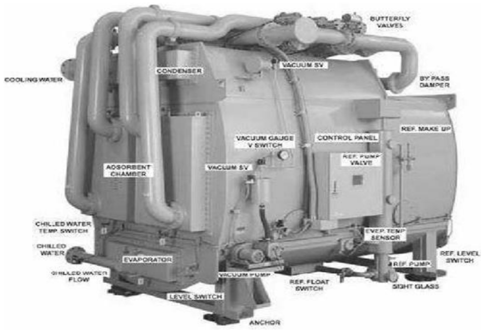

Fig. 19 Nishiyodo Kuchouki Co Ltd Adsorption chiller [75]

5 CHALLENGES AND FUTURE RESEARCH DIRECTIONS

A comprehensive plethora of the development trend in solar adsorption refrigeration technology has been extensively presented in this work. However, it is clearly evident that in spite of the numberless attempts made by various researchers to improve its performance and as well maintain its presence in the market, it appears not yet ready to compete with the traditional vapour compression cooling systems due to identified technical and economic limitations like low COP, high initial cost, poor heat management, large volume and weight, intermittency issue, operating conditional variations and automatic control which seem difficult to overcome. Notwithstanding, adsorption cooling technology is not just energy saving but also eco-friendly.

Howbeit, calling to mind the progresses made in adsorption technology over the past decades, it seems the performance of the basic cycle can no longer be significantly improved. Even though higher performances seemed to have been recorded by the advanced cycles, however, they usually require a continuously circulating cooling/heating medium and too many valves to operate uninterruptedly. All these modifications make the systems more complex and expensive. Honestly speaking, among the adsorption cycles mentioned above, the heat and mass recovery cycle is one of the easiest cycles to be used in the practical systems. Most of the others are just studied in laboratory [29] or theoretically. They all are often limited by the problem of low COP.

Deterioration of the solid desiccant's adsorption capacity is another allied phenomenon to look into because it impacts the widespread utilization of the adsorption refrigeration technology. In addition to other problems identified in this work, this deterioration issue caused by the frequent switching between adsorbers and desorbers, is yet to be addressed in the literatures. Solid desiccants are used in both adsorption refrigeration and open cycle desiccant dehumidification applications. However, unlike the adsorbent of the rotary solid desiccant dehumidifier which has a long term usage capability, the capacity of the solid desiccant severely deteriorates after a short period of utilization due to: frequent switching, larger pressure difference and faster speed between adsorption and desorption. This intense energy exchange on adsorbents micropores gradually changes the surface microstructure which eventually impacts the adsorption capacity adversely.

Therefore, researches should be intensified in order to mitigate these crucial bottlenecks that make the system not yet competitive with the convectional VCRS.

6. CONCLUSION

In this review paper, a comprehensive plethora of the developmental trend in solar adsorption refrigeration systems ranging through its allied technologies, cycles and applications has been extensively presented. Furthermore, major limitations of the existing systems were also identified and possible future potentials for research directions were also suggested for the widespread application of the technology. This review which includes the current progress in solid desiccant solar refrigeration technology from the latest published journal papers available through ScienceDirect, open access manuscripts, Google scholar and patent is believed to provide the required impetus for fast tracking its further development and wide application.

ACRONYMS/ABBREVIATIONS

AC - activated carbon

ARC-adsorption refrigeration cycle

ARCs- adsorption refrigeration cycles

ARS- adsorption refrigeration system

CFCs- chloro-fluoro-carbons

COP – coefficient of performance

CPC - compound parabolic collectors

CTAR - Constant temperature Adsorption Refrigeration

DNI-direct normal irradiation

HCFCs- hydro-chloro-fluoro-carbons

PTC - parabolic trough-solar collector

SAR - solar adsorption refrigeration

SARS - solar adsorption refrigeration systems

SCOP - solar coefficients of performance

SCP – specific cooling power

SDRS- solid desiccant refrigeration systems

VCRS-vapour compression refrigeration system

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