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Solar-Driven Air-Conditioning Cycles: A Review

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دورات عمل تكييف الهواء المبنية على الشمس / استعراض

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الخلاصة: ان معظم انظمة التبريد التقليدية تعمل بواسطة احتراق الوقود الاحضورى وبالتالي تؤدي الى انبعاث الملوثات الضارة بيئيا. يضاف الى ذلك، ان العديد من أنظمة التبريد تستخدم السوائل المبردة، وهي ايضا تشكل خطرا على البيئة من ناحية تسببها بمشاكل بيئية عالمية كارتفاع درجة الحرارة واستنزاف طبقة الأوزون. ان التطور في تهجين نظام التكييف المبنى على الشمس اصبح من الاهمية على اساس ان استغلال مثل هذه الانظمة قد قلل الطلب على الكهرباء وخصوصا في اوقات الذروة. هذه الورقة تستعرض مختلف دورات التبريد وتلخص العمل التي تم القيام بة على أنظمة تكييف الهواء العاملة بالشمس.

المفردات المفتاحية: الطاقة الشمسية، دراسات التبريد، نظام تكييف الهواء، معامل الاداء.

Abstract: Most conventional cooling/refrigeration systems are driven by fossil fuel combustion, and therefore give rise to emission of environmentally damaging pollutants. In addition, many cooling systems employ refrigerants, which are also harmful to the environment in terms of their Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). Development of a passive or hybrid solar-driven air-conditioning system is therefore of interest as exploitation of such systems would reduce the demand for grid electricity particularly at times of peak load. This paper presents a review of various cooling cycles and summarises work carried out on solar-driven air-conditioning systems.

Keywords: Solar energy, Cooling cycles, Air-conditioning system, and coefficient of performance (COP)

1. Introduction

In recent years, the increased usage of air conditioning systems in hot/humid climates has resulted in a significant increase in demand for primary energy during summer months. In some countries, blackout situations have occurred during periods of peak load due to overburdened distribution networks.

Most air-conditioning systems operate using a vapour compression cycle and are electrically driven by means of fossil fuel. This results in a large amount of CO_2 being released to the atmosphere, which contributes strongly to global warming. The steady rise in the temperature of the Earth's atmosphere will of course exacerbate the demand for air-conditioning, thus creating a vicious cycle in terms of cooling and electricity demand. Use of solar energy to power air-conditioning systems would allow this cycle to be broken as peak cooling loads coincide with maximum available solar power.

Various cycles can be used to provide cooling. Each has some advantages, but also some limitations in comparison with other cycles. The following section presents a brief description of each cycle followed by a comparison with other methods. The technical, environmental and economic issues associated with various solar-driven cooling/refrigeration systems are also discussed.

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2. Types of Cooling Cycle

2.1 Conventional Refrigeration (Vapour Compression Cycle)

The most widely used refrigerators are those, which use a liquefiable vapour as the refrigerant. The evaporation and condensation processes take place when the fluid is receiving and rejecting latent heat at constant temperature and pressure. Fig. 1-b shows the schematic diagram of a vapour-compression cycle, while Fig. 1-a illustrates the cycle on a P-H diagram. The ideal cycle can be described as follows: At point 1, the refrigerant is a low-pressure vapour. The vapour pressure as well as the temperature increases to point 2 by the effect of the compressor through path 1-2 (isentropic compression). From point 2 to point 3, the vapour passes through the condenser where heat is removed, condensing the vapour to a sub-cooled liquid (or saturated liquid) at constant pressure. From point 3 to point 4 the high-pressure liquid refrigerant is throttled through an expansion device (valve), where

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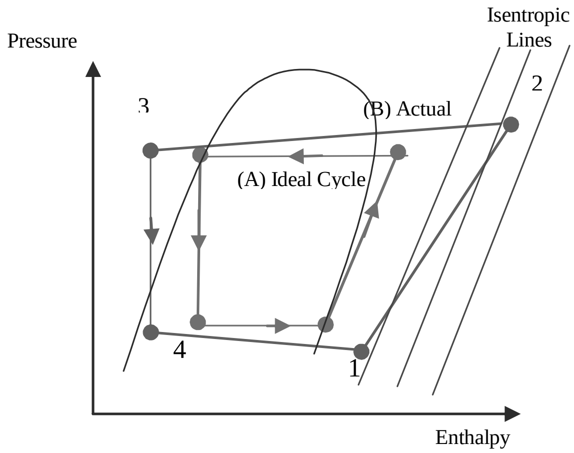

Figure 1-a P-H diagram for vapour compress cycle

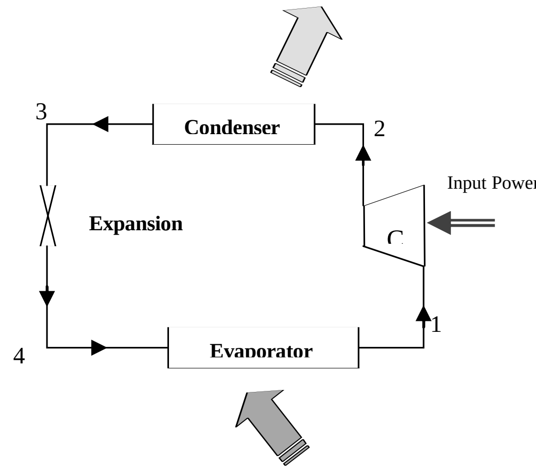

Figure 1-b Schematic diagram for vapour compre-ssion cycle

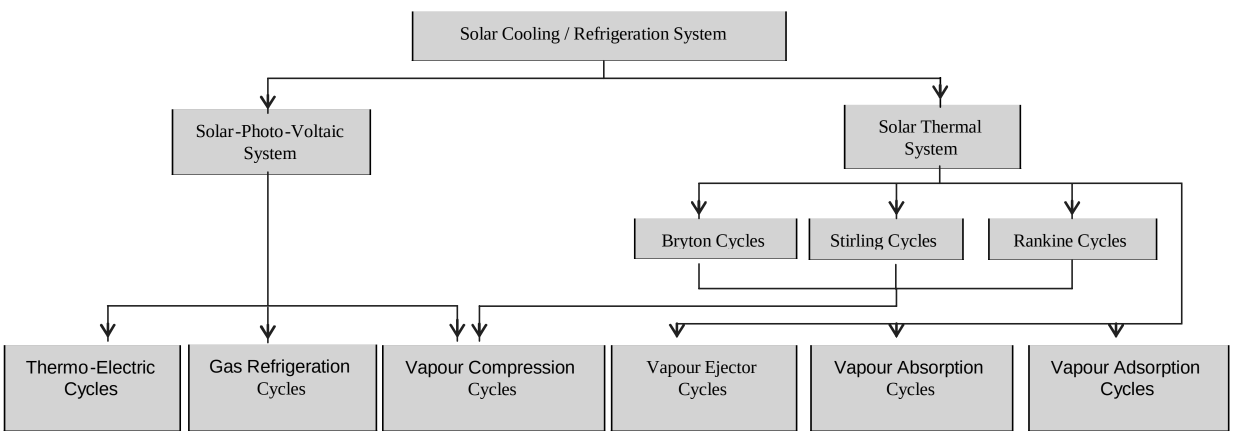

Figure 2. Classification of solar refrigeration cycles

some liquid flashes to vapour, forming a two-phase mixture at low pressure and temperature. The two-phase (liquid-vapour) mixture flashes to vapour on entering the evaporator, where the heat necessary for evaporation is taken from the space being conditioned.

For the cycle to be termed ideal, all the individual processes would need to behave exactly as specified above. In the actual cycle however, pressure loss occurs in the evaporator and the condenser. In addition, the compressor does not operate isentropically (adiabatic and reversible), *ie*. the compression process is an irreversible process (Fig.2).

The refrigerant does not enter the compressor in a dry saturated condition. Generally, it has a small degree of superheating to avoid droplet formation on entering the compressor that could cause impact damage. The actual process can be represented in Figure 2-a by shifting point 1-a little to the right. The condensed vapour can be cooled at constant pressure (condenser pressure) to a temperature below the saturation temperature, *ie*. line 3-4, which represents the throttling process and can be moved to the left. This results in an increase in the refrigeration effect. The effect of under-cooling/sub-cooling of the refrigerant after the condenser would offset the performance reduction slightly.

Most existing cooling and refrigeration systems employ a vapour compression cycle due to its high COP. However, these systems are now less attractive as the chlorofluorocarbons (CFCs) refrigerants have a high ozone depletion potential (ODP) and a high global warming potential (GWP). Other problems associated with vapour compression cycles include:

- Hazardous working fluids.
- High consumption of energy, since the compressor is powered by electrical energy.
- Lifetime of the system is relatively short, due to wear of the moving parts.
- Electrical energy is usually supplied by fossil fuel combustion, producing greenhouse gases and other pollutants.
- Noise and vibration due to moving parts.

Adaptation of the vapour compression cycle to allow use of environmentally non-damaging refrigerants has been encouraged to protect the ozone layer and reduce global warming. The use of thermal energy, such as industrial waste heat, geothermal and solar energy has also been investigated as a mean of alternative source of energy for the refrigeration cycle in order to reduce the demand of primary energy from fossil fuels.

A number of refrigeration cycles have been devised to utilize solar energy as a clean and renewable energy source. The following section provides an overview of refrigeration cycles that could be integrated with solar energy and utilized in place of a vapour compression refrigeration cycle (see Fig. 2). The primary benefit of solar powered systems is reduced demand for grid electricity in the afternoon when load is at its peak.

A solar-driven vapour compression cycle is one solution to some of the problems, mentioned previously, *ie*; high consumption of primary energy and negative environmental impact of some emissions. The Rankine cycle and photovoltaic can be regarded as the two main techniques for driving a vapour compression cycle using solar energy.

Many refrigerants traditionally used in vapour-compression systems exhibit excellent thermo-physical properties, but have been banned because of their adverse environmental impact, *ie*. high ODP and GWP. Some refrigerants have negligible ODP but still have a considerable GWP as illustrated in Table 1 (US EPA http://www.epa.gov/).

Table 1. ODP and GWP of CFC, HCFS and HFC refrigerants

Refrigerant Type	Refrigerant	ODP*	GWP**
CO_2	R744	0	1
CFC	R11	1	4000
	R12	1	8500
HCFC	R113	0.8	5000
	R22	0.05	1700
HFC	R401b	0.035	1190
	R507	0	3800
	R123	0.02	93
	R134a	~0	3200
	R23	0	12100

*ODP quoted relative to R11 and R12, the ODP of which has been designated as1.
** GWP quoted relative to CO_2, the GWP of which has been designated as1.

This has created the need to identify new, environmentally friendly refrigerants for vapour compression systems. The most important feature of these refrigerants include:

1. Non-toxic,
2. Non-flammable,
3. Non-corrosive
4. Very low freezing temperature (well below evaporator temperature)
5. Very high boiling temperature (well above condenser temperature)

For example, the first two criteria are not satisfied by ammonia, which also corrodes copper pipes, and CO_2 does not fulfill the fifth condition.

2.1.1 Rankine vapour compression cooling cycle

A Rankine vapour compression cooling cycle consists of two component cycles, *ie*. the Rankine power cycle drives the vapour compression cooling cycle. The basic principle of this combined cycle is illustrated in Fig. 3. The working fluid (liquid state) is heated under high pressure in the boiler of the Rankine cycle by the collected solar radiation. The high-pressure vapour is then expanded through a turbine to a lower pressure and temperature, which results in mechanical work at the turbine shaft. The vapour is then condensed and returned to a liquid state under the same pressure. Pumping the liquid back to the boiler allows the cycle to be repeated. The mechanical work generated at the turbine shaft is used to drive the compressor of the vapour compression cycle. Coupling these two cycles could be carried out mechanically through a common shaft, or electrically using electric generator, which would supply electricity to the compressor and other electrical loads. Flat plate and evacuated solar collectors would be suitable for use with the Rankine power cycle (Curran, 1992).

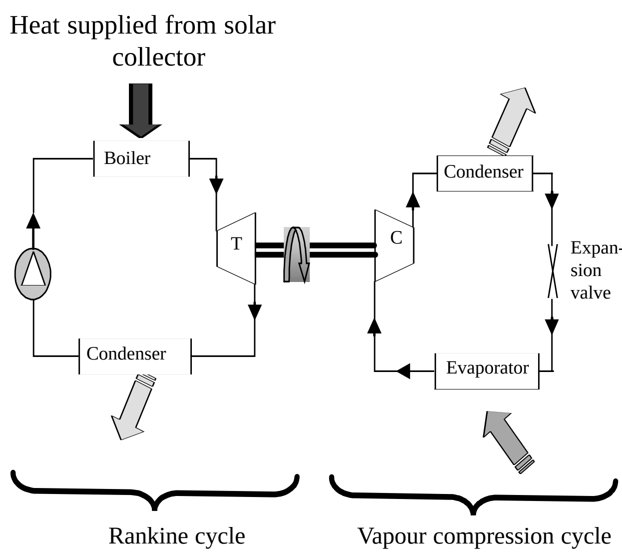

Figure 3. Schematic diagram of Rankine-vapour compression cooling cycle

2.1.2 Photovoltaic-driven vapour compression cooling cycle

This cycle has two main configurations. The first uses direct current, DC, supplied directly from the photovoltaic, PV, and the second uses alternating current, AC, supplied by the use of an inverter to convert the DC generated by the PV. The second configuration is preferable, as it is possible to connect it to the national grid (with higher efficiency) without the need for expensive battery storage. DC- driven vapour compression systems are suitable for rural areas, where buildings may be remote from the electricity grid.

The Rankine cycle is the most efficient thermodynamic cycle, compared with Stirling and Bryton cycles, for driving a vapour compression cycle. On the other hand, it is significantly more complex than a photovoltaic driven vapour compression cycle from an energy conversion

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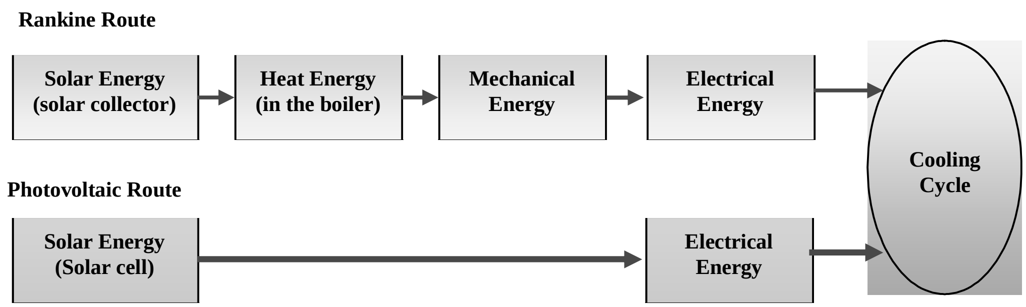

Figure 4. Schemtic diagram of Rankine cycle and photovoltaic cycle routes

aspect. In other words, a Rankine cycle involves two more conversion processes, compared with a photovoltaic cycle, to operate the cooling cycle as illustrated in the Fig. 4.

In addition to providing direct electrical energy, a PV system has several other advantages:

- No CO_2 emission
- Very long service life due to the absence of moving parts (estimated as longer than 20 years)
- Reliable; since it operates at very low irradiance (even on cloudy days)
- Energy payback time (EPT) is very much shorter than its lifetime (Ohnishi *et al*., 1995)

EPT can be defined as the number of years that are required for the cell modules to generate the same amount of electric power as was consumed in their fabrication. This depends on conversion efficiency and production volume. At a production volume of 10 MW/year in the case of a 8% conversion efficiency solar cell, the EPT is estimated to be 1.2 years for a-Si solar cell and 4 years for poly-Si solar cell (Ohnishi *et al*., 1995).

However PV systems also have some disadvantages:

- Higher initial cost
- Land displacement
- Visual intrusion.
- Reduction of performance at higher temperatures.

It should be noted that the cost of PV technology is likely to fall significantly as production volumes increase and improvements in efficiency are also probable as technology develops. As an example, a protection against over-current for a PV driven air-conditioning system has been developed (Wagdy *et al*., 1995).

PV-cells can also be integrated in buildings as architectural element in an aesthetically pleasing manner, so land displacement and visual intrusion can be alleviated. Cooling of PV cells in order to maintain their efficiency can be accomplished by attaching a PCM (phase change material) to the back of the modules, or by passing a stream of air through a ducting from the back side so that the hot air generated may be used in other utilities (Morgan and Prasad, 2001).

Jubran *et al*. (2003) has carried out a feasibility study on various PV systems namely; Stand-Alone PV (SAPV), a hybrid Grid PV (GPV), Grid PV Wind turbine (GPVW) and PV Wind turbine (PVW) for supplying the power requirements of a window-type air conditioning system under hot-arid climat (Oman climate condition on 2003). It was found that the hybrid system (GPVW) was the preferred system with minimum net present cost but higher capital cost depending on the wind speed. In other words, the GPVW system has the least total net present cost among all systems at around $33,000 with a capital cost of $39,500 for 5 m/s wind speed. Increasing the wind speed to 8 m/s resulted in a further decrease in the net present cost to less than $10,000, while the capital cost increased from $39,500 to around $56,500.

2.2 Absorption Cooling Cycle

The absorption refrigeration cycle is well known. Ferdinand Carre (Chad *et al*., 1995) developed the first absorption machine in the mid-nineteenth century. The key difference between this cycle and a vapour-compression cycle is the process by which the low-pressure refrigerant (vapour) is transformed to a high-pressure vapour, path 1-2 (see Fig.5-a or 5-b). In an absorption cycle, the low-pressure vapour is absorbed into an absorber (either solid or liquid) at low pressure, pumped to a high pressure, and then heated to produce a high-pressure vapour. The compressor function in an absorption cycle is commonly referred to as a thermal compressor, chemical compressor, or thermo-chemical compressor (see Fig.5-b), whereas in a vapour-compression cycle, any type of mechanical compressor (reciprocating, rotary, screw, …etc.) can be used.

In order that the sequence of events should be continuous, it is necessary for the refrigerant to be separated from the absorbent and subsequently condensed before being returned to the evaporator. Path 1-2 in the absorption cycle can be described as follows: the low-pressure, low-temperature refrigerant vapour enters the thermal compressor at point 1, and is absorbed into a solution (for example) at (2-0). The absorbent-refrigerant mixture is then pumped, via the heat exchanger, to the generator at point (2-3), where the refrigerant vapour is separated from the absorbent solution by heating, This process generates high-temperature high-pressure refrigerant vapour which is then passed to the condenser and the weakened

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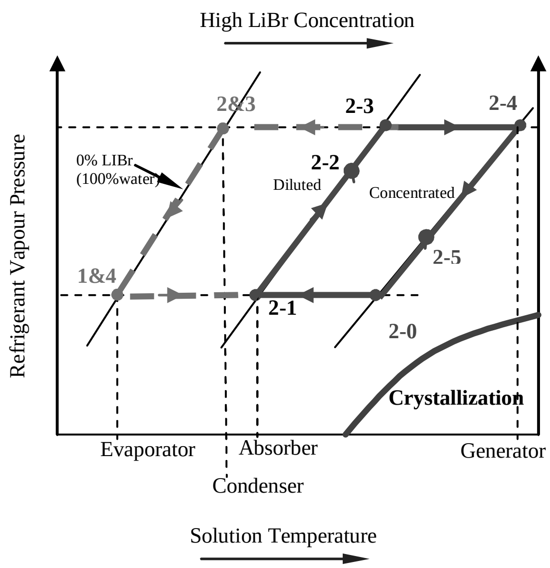

Figure 5-a PTX chart for absorption refrigeration cycle (for single effect)

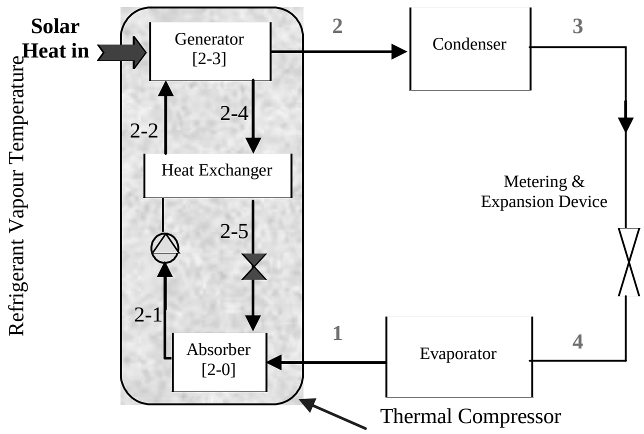

Figure 5-bSchematic diagram absorption refrigeration cycle (single effect)

absorbent solution is returned to the absorber.

A (P-H) diagram cannot be used to graphically show the absorption cycle. Instead, a chart that includes the solution concentration -a PTX equilibrium chart- has been used. Fig. 3-a shows the PTX equilibrium chart, which shows the relationship between the refrigerant vapour pressure and its corresponding temperature, the solution temperature and the concentration of the solution.

Currently two absorbent-refrigerant systems are widely employed, namely, lithium bromide (LiBr)-water (aqueous) system and water (aqueous)-ammonia system (AAR). In the first system, the LiBr, a salt, is the absorbent and the water is the refrigerant, while in the second system, the water is the absorbent and the ammonia is the refrigerant. Absorption machines are categorized either by the number of effects, as in LiBr-water refrigeration system, or by the number of stages, as in an Aqueous-Ammonia Refrigeration (AAR) system, to increase their COP. In this guide, an effect refers to the number of times the input heat is used by the absorption machine, either directly or indirectly (Chad, *et al*. 1995). In single-effect system, the input heat is used once. In double-effect system the input heat is used twice and so on. Stage refers to the number of evaporator/absorber pairs at different temperatures in an absorber machine. The cooling outputs of these two systems are different. The cooling output for a LiBr system is (4)-(38) ^{o}C for a single-effect and (4)-(27) ^{o}C for a double-effect, and this is suitable for air-conditioning applications. For an AAR system the cooling effect is (-51) - (4) ^{o}C and is suitable for refrigeration applications.

The popularity of the absorption system has been influenced by economic conditions and technology breakthroughs from competing technology. The benefits of absorption systems over vapour-compression systems can be summarized as follows:

Existing absorption systems however, do have some

- Absorption systems do not contribute to ozone depletion and may have less impact on global warming.
- They are quiet and vibration free and hence have a longer operational lifetime.
- They have a lower electrical need compared to vapour-compression systems (*ie*. much less work is required to compress liquid rather than compress vapour).
- Diversity of energy source (*ie*. absorption systems can be driven by waste heat, solar energy or hybrid sources (e.g. solar/gas).

limitations in that they can be used only with a few refrigerant/absorbent combinations, principally water/LiBr. Concentrated LiBr solutions have a relatively high crystallization temperature and can freeze inside the chiller unit. They are corrosive to metals and are very expensive. Many refrigerant/absorbent combinations have been mentioned in the literature, but these have similar disadvantages to LiBr solution. However, many limitations can be overcome by the use of a new working fluid namely, water/potassium formate (H2O/HCOOK) in absorption systems (Riffat *et al*., 1999). The physical properties of potassium formate present many benefits, *ie*. it is less corrosive, less expansive to manufacture and has a lower density and viscosity than absorbents such as LiBr.

Other challenges facing solar-driven absorption systems are:

Over the last three decades various attempts have been

- High initial cost,
- Low COP
- Bulky and heavy
- Difficulty in storing high temperature heat (i.e. short period of solar irradiance per day, hence not yet competitive with gas-fired or electricity driven A/C systems.

made to improve the performance of solar-driven absorption systems through improvement of the major components of the system, *eg*. absorbent material, chiller, solar collector and storage tank. In order to achieve continuous operation and improve system performance, a hot water storage tank is essential. It has been reported by (Kreider and Kreith 1981) that using two hot storage tanks maintained at different temperatures would allow the system to operate more efficiently. Partitioning a single hot water storage tank into an upper part and a lower part has also been investigated (Li and Sumathy, 2001). In the morning, the upper part would operate the system, while the whole tank would serve as a heat reservoir in the afternoon.

The efficiency of the absorption cycle can be increased by raising the operating temperature through multi-effects. The typical operating temperature for a single effect is in the range of 60 to 80 ^{o}C, while for a double effect it is 100 to 160^{o}C. These ranges of operating temperature are highly suitable for solar energy applications using different solar collector techniques. Double or triple effect systems however, are extremely expensive, due to the cost of high temperature collectors. But the question arises here: Are multi-effect systems of higher COP, more suitable for solar powered cooling than their single-effect counterpart, with the availability of high temperature gas-fired systems. This question has been studied (Grossman, 2002) by conducting a comparison between single-, double-, and triple-effect systems, using LiBr-water chillers producing chilled water at 7 ^{o}C with cooling water supplied at 30 ^{o}C (refer to Table 2). It is indicated that the total system cost is mainly dependent on the solar part of the system. It is also noticed that a double-effect system is cost and performance competitive with the single -effect system.

2.3 Desiccant Cooling and Open Cycle System

A desiccant cooling system is basically an open absorption cycle, utilizing water as the refrigerant in direct contact with air. The term 'open' indicates that the refrigerant is disposed from the system after supplying the cooling effect (*ie*. without air circulation), while the same amount of refrigerant is replaced in an open-ended loop as illustrated in Fig. 6. Add in another configuration, an open solid desiccant cycle could be operated in a circulation mode, where the room air is circulated and the ambient air is used only for regeneration (*ie*. does not enter the room).

The main advantages of these systems over closed absorption systems are as follows (Grossman, 2001):

It is worth mentioning that the major merits of solid-

- They operate at ambient temperature, and not at vacuum or an elevated pressure
- Heat and mass transfer between the air and desiccant takes place in direct contact
- Cooling and dehumidification of the conditioned air may be provided in variable quantities.

desiccant cooling systems include the improved indoor air quality and simplicity of construction and maintenance.

On the other hand, the major limitation of desiccant systems is the low COP (0.5-1.0) relative to the closed system, due to inefficient regeneration. Also their performance may be influenced by variation in weather conditions. Periodic replacement of the desiccant is also necessary owing to contamination by air pollutants. A desiccant wheel (honeycomb rotary bed impregnated with sorbent material such as silica gel, zeolites or carbon) may be used in the solid desiccant system to ensure the continuity of the dehumidification process (*ie*. adsorb the water vapour from the moist air passing through it).

Both solid and liquid desiccants can be used to remove latent heat (*ie*. dehumidification process), while the evaporative cooler removes the sensible heat. This is preferable to maintain comfortable humidity levels in the conditioned space. The disadvantage of the Liquid desiccant (sorbent) may be the carryover potential of sorbent in the air, which may pollute the air and reduce the amount of available desiccant. Liquid desiccant systems may employ packed towers, packed beds or a spray chamber (Mongar, 1997). This type of system has a number of advantages over solid desiccants, including:

A number of solar-driven air-conditioning systems

Table 2. Comparison of single-, double- and triple-effect absorption chillers for solar-powered air conditioning systems (Grossman, 2002)

	(1) Typical COP	**(2) Heat source temp. [^{o}C]**	**(3) Solar heat required [kW]***	**(4) Type of collectors**	**(5) Typical collector cost [S/m^2]**	**(6) Heat collected per day [kWh/m^2]**	**(7) Collector area required [m^2]**	**(8) Solar system cost [S]***	**(9) Absorption chiller cost [S]***	**(10) Total system cost [S]***
Single-effect	0.7	85	1.43	Flat-plate	110	1.53	7.48	1234	200	1434
Double-effect	1.2	130	0.83	Flat-plate/CPC	160	1.31	5.07	1216	175	1391
Triple-effect	1.7	220	0.95	Evac-tube/ concentrating	400	1.05	4.49	2694	165	2859

* Indicates figures per kW of cooling capacity

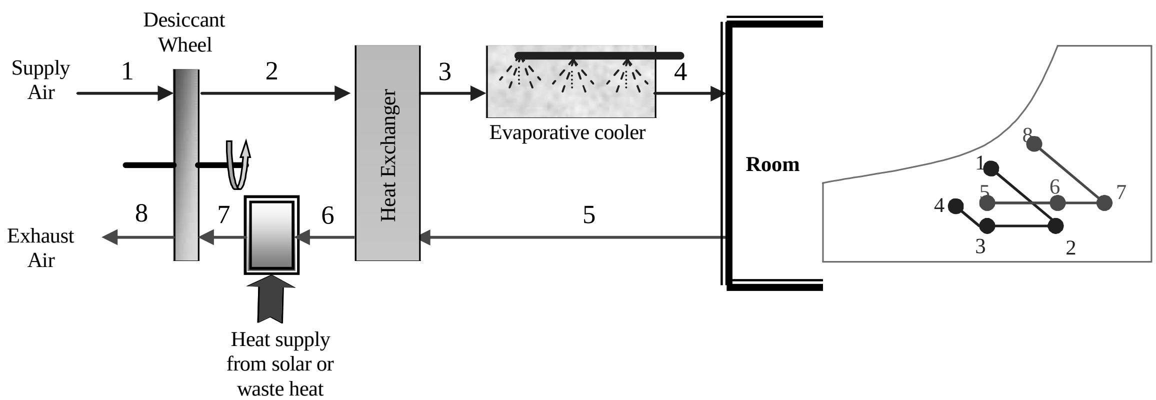

Figure 6. Desiccant cooling system

- Lower regeneration temperatures (60 – 80 °C for liquid desiccant compared to100 –150 °C for solid desiccant) (ASHRAE, 1997).
- Suitability for dust removal by filtration
- Greater mobility by pumping the sorbents
- Lower pressure drop of air across the desiccant.
- Dehumidification of greater quantities of air per unit mass than solid desiccant (*eg*. lithium chloride can absorb up to 1000% its dry mass weight of water (ASHRAE, 1997).

using liquid desiccant have been constructed (Wood, 1986; Lenz *et al*., 1985). A novel-solar powered open cycle Dehumidifier-Evaporator- Regenerator (DER) system has been developed (Gershon Grossman, 2002) and in contrast with a closed-cycle absorption system of double or triple effect more this fase found to be suitable for use with relatively low temperature heat sources such as a flat plate solar collector. It produced both chilled water, and cold, dehumidified air in variable quantities. A novel air-conditioning system using a liquid desiccant, in an open cycle, has also developed (Armando *et al*., 1999). The system employed needle-impeller rotors to improve heat and mass transfer in the absorber and evaporator units (Riffat, patent) as shown in Fig. 7. The system has a substantially lower initial cost than a solid desiccant system (using desiccant wheel), due to the reduction in system volume. It also has the potential to compete with a conventional vapour compression system owing to its energy efficiency, low capital cost, and its compactness.

2.4 Adsorption Cooling Systems

The basic principle of operation of adsorption and absorption cycles is similar. They do however, differ in two respects (Anyanwu, 2004). The first is in the nature of the sorbent. An adsorption cycle uses only solid adsorbent, and as a result is characteristically intermittent in operation. An absorption cycle on the other hand, may use either solid or liquid absorbent and can therefore operate intermittently or continuously. The second difference is the process of refrigerant accumulation on the adsorbent, since the refrigerant is trapped in the micro-pores of the solid adsorbent. The duration of the cooling cycle is also significantly longer for single bed adsorption systems. For the multi-bed system, the cycle time could be short. The main advantages of an adsorption system over existing absorption systems are as follows:

- Simple construction and can be built on a small scale
- Can utilize heat at lower temperatures
- No corrosion problem
- No need for solution pump
- The system units are totally autonomous. In some cases for the absorption systems, precise temperature regulation is required, which may be difficult to achieve with solar heating (Meunier, 1994).

On the other hand, the COP of the adsorption chillers is lower than that of absorption systems, and as they are more expensive, their commercial availability is still limited. This is in addition to less efficient heat transfer in solid adsorbent beds.

Generally, adsorption is a process in which fluid molecules are trapped on the surface and within the pores of a solid. The pore structure of interest for refrigeration applications is micro-pore (radii <15 Å). There are two main types of solid adsorption process: physical and chemical adsorption (physisorption and chemisorption, respectively). Physisorption occurs as a result of relatively weak Van der Waals' attraction forces binding the adsorbing molecules to the solid phase, and predominants at low temperatures (Anyanwu, 2004). Chemisorption is accompanied by a chemical reaction, which occurs when covalent or ionic bonds are formed between the adsorbing molecules and the solid substances. This is therefore characterized by comparatively high energies of adsorption.

There are many adsorbent-adsorbate pairs used for air-conditioning/refrigeration purposes, as illustrated in Table 3 (Sumathy *et al*., 2003) The commonly used adsorbents in air-conditioning are silica gel and zeolite, with water as an adsorbate (refrigerant). Silica gel/water is the most common pairing particularly in solar driven system, due to its lower regeneration temperature, which is below 100 °C,. For a Zeolite/water system this temperature is 170 °C (Papadopoulos *et al*., 2003).

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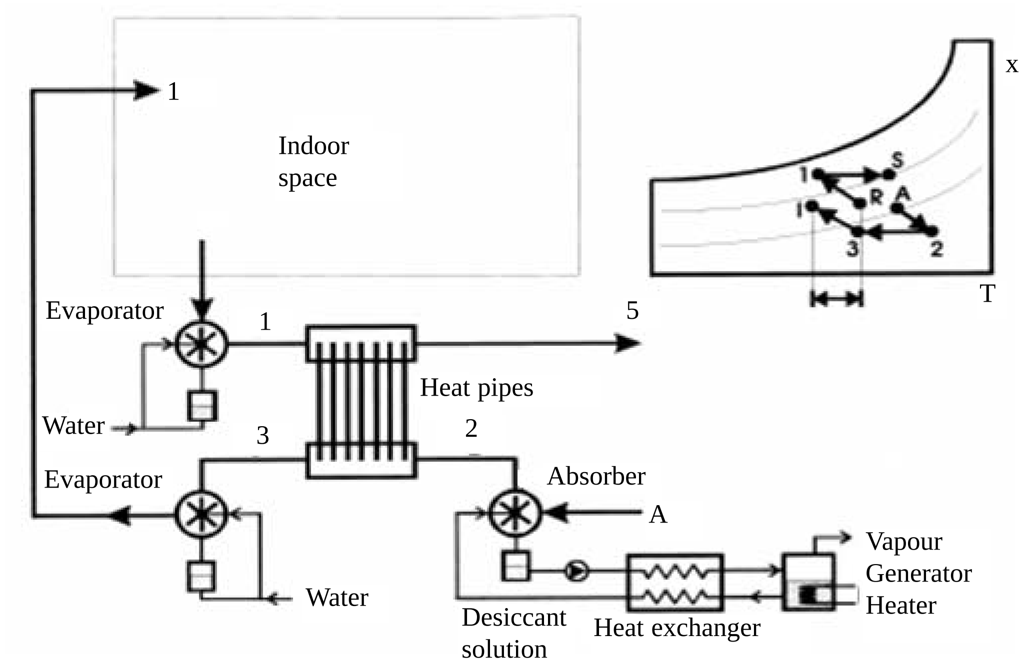

Figure 7. Desiccant air-conditioning open cycle and air evolution in temperature (T)-water content (x) graph (Armando *et al*., 1999)

Table 3. Absorbent/adsorbate pairs and heat of adsorption (Sumathy et al. 2003)

Adsorbent	Adsorbate	Heat of adsorption (kJ kg $^{-1}$)	Remarks
Activated alumina	Water	3000	Water is applicable except for very low operating pressures
Zeolite (various grades)	Water	3300-4200	Natural zeolites have lower values than synthetic zeolites
	Ammonia	400-600	
	Carbon dioxide	800-1000	
	Methanol	2300-2600	
Silica gel	Methyl alcohol	1000-1500	Not suitable above 200^{o}C
	Water	2800	Used mostly for desiccant cooling
Charcoal	C_2H_4	1000-1200	Reacts at approximate 100 ^{o}C. Ammonia and methanol are not compatible with copper at a high temperature
	Ammonia	2000-2700	
	Water	2300-2600	
	Methanol	1800-2000	
	C_2H_5OH	1200-1400	

Adsorption systems may be intermittent or continuous. The use of a single bed results in intermittent cycle operation due to changing between adsorption and desorption stages. A description of one-bed cycle operation is as follows: The refrigerant vapour, which has been evaporated in the evaporator, is adsorbed into a solid adsorbent bed, which acts as a sponge. When all the refrigerant vapour has left the evaporator, it can be recovered from the adsorbent by heating it in the adsorber/generator chamber. The refrigerant vapour is extracted and then cooled and condensed in the evaporator/condenser chamber. Intermittent adsorption can be overcome by using multiple adsorbent beds with one in operation while the other is regenerated.

Critoph and Tamainottelto (1997) have studied the performance of a solar adsorption refrigerator experimentally for three different configurations of glass cover of a flat plate solar collector. Similarly, the performance of a solar-powered continuous (two bed) adsorption air-conditioning system driven by a flat plate solar collector has been investigated (Yong and Sumathy, 2004). Collectors used in the water heating system, during winter, were utilized as the heat source to energize the air-conditioning system during summer. The working principle of the system is shown in Fig. 8. In the desorption phase, adsorber A is connected to tank 1 to heat and desorb the refrigerant from the adsorbent. The adsorption phase is conducted in adsorber B, which is connected to tank 2, to adsorb the refrigerant vapour leaving the evaporator at low pressure. The condensed refrigerant leaves the condenser and flows to the evaporator. In order to increase the efficiency of the system and to attain continuous cooling, the two adsorbers are connected to each other after each desorption cycle, to recover heat.

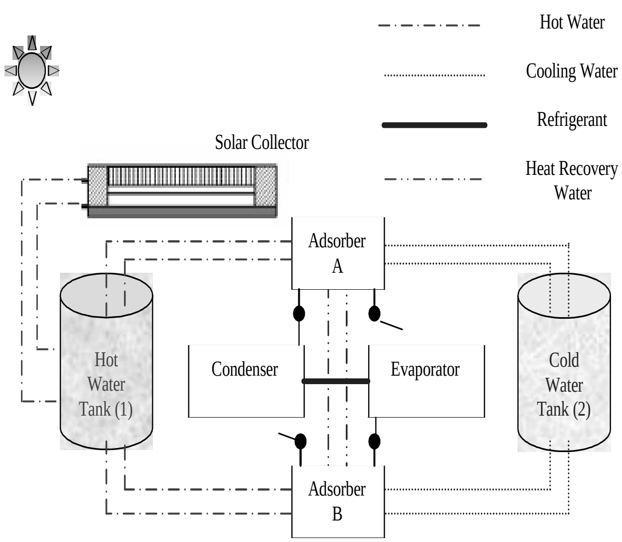

Figure 8. Solar powered continuous (two beds) adsorption air-conditioning system (Yong and Sumathy, 2004)

Considerable effort has been made to improve the heat regeneration efficiency of the system. Typical cycles are listed as follows (Hai-Ming Lai, 1999):

1. Heat recovery cycle (Meunier, 1985; Van, 1995): Heat is recovered by an additional regenerative period: circulating a heat transfer fluid (HTF) between the two adsorbers until they reach a common temperature.
2. Thermal wave cycle (Shelton, *et al*. 1989): Heat is stored and regenerated using sharp temperature fronts (thermal wave) in the adsorbent beds. Theoretically this would obtain more than 80% of heat recovery from the bed being cooled.
3. Flow reversal cycle (Dong, 1995; Lai and Li, 1996): In terms of the concept of thermal wave, internal heat regeneration is produced within one bed by forced unsteady-state operation achieved by periodically switching the flow direction of the HTF.
4. Convective thermal wave cycle (Critoph,1994): This is different to the traditional means of heat transfer carried out by heat conduction described as above three cycles (1-3).The heat and mass transfer of this cycle are intensified by using forced convection between the refrigerant and adsorbent. The heat regeneration is performed via a gas-gas heat exchanger or inert packed beds.

A detailed review of heat regeneration cycles of adsorption systems has been presented by (Sumathy *et al*., 2003). A Periodic Reversal Forced Convective Cycle has been suggested (Lai and Li., 1999) based on the combination of cycles 3 and 4 listed previously, and a mass recovery cycle has been found to be effective for low regenerating temperatures (Pons *et al*., 1999; Wang, 2001).

A novel strategy in mass recovery has been proposed (Akira *et al*., 2004) to improve cooling capacity. This is completely different from the conventional mass recovery cycle, in that the heating and cooling processes during the mass recovery process, do not exist. In this cycle, the adsorber kept in cooling process, while the desorber is continuously provided with hot water. This cycle is very applicable for solar heat source/low temperature waste. A brief description of the working principle of the two-bed system is shown by the diagrams in Fig. 9. The cycle has six modes, which can be divided into two similar parts (*ie*. the first three modes are analogous to the next three modes), where the adsorption and desorption processes are switched. In the first mode the evaporator and heat exchanger (HEX1) are connected via valve 2 (V2) in the adsorption-evaporation process, while the condenser and (HEX2) are connected via V3 in desorption-condensation process. All other valves are closed. In the second mode, the desorbed refrigerant in HEX2 moves to the adsorber (HEX1) through V5 by the effect of differential operating pressure on the two heat exchangers, while all other valves are closed. The third mode is a relax mode, where all the valves are closed and the heat exchangers are switched (*ie*. HEX1 is warmed up and HEX2 is cooled down until they become almost equal pressures to the CON and EVA, respectively). The fourth mode is then started, where V1 and V4 are opened. This mode is similar to mode 1. Actually, the only difference between this cycle and the conventional single stage cycle is V5 and the pipe connecting the heat exchangers (*ie*. the 2nd and 5th modes do not exist). The same investigators (Alam *et al*., 2004) have also studied a four-bed mass recovery system, which provided improved performance. The cascading feature of the heating and cooling source developed different pressure levels, which in turn enhanced the refrigerant mass circulation.

Combination of commonly used solar collectors (flat plate, evacuated tube and solar air collectors) with sorption refrigeration/cooling systems can be evaluated by a collector efficiency-driving heat temperature diagram as shown in Fig. 10 (Henning, 2000). It can be seen that only vacuum tube collectors are applicable for a double effect absorption system, while flat plate or evacuated tube collectors can be used for adsorption and single effect absorption systems. It is clear from the diagram that the generation temperature for desiccant cooling is relatively low, and so a solar air-collector would be suitable for this system.

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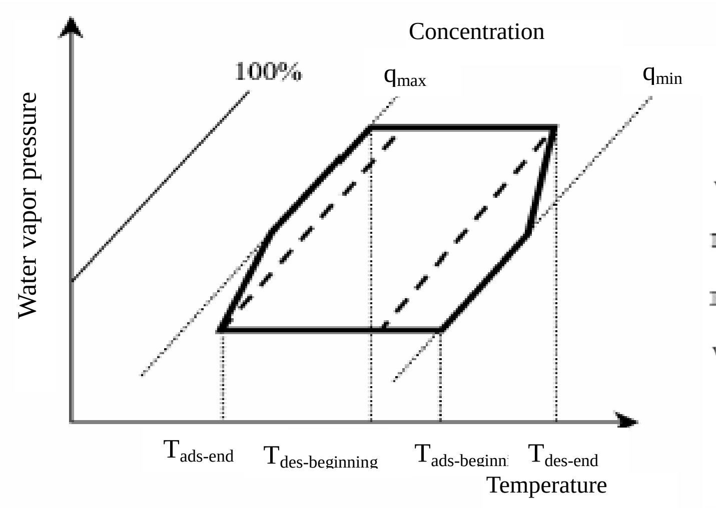

Figure 9-a. PTX diagram for mass recovery cycle

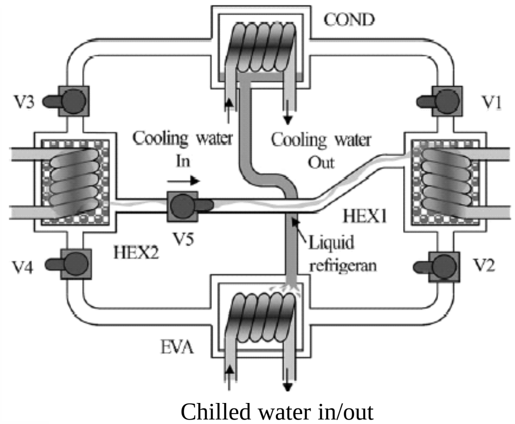

Figure 9-b. Schematic of mass recovery absorption refrig4eration cycle, second made (Alam, 2004)

2.5. Ejector Cooling Cycle

An ejector-cooling cycle is one of the alternatives to a vapour-compression cycle, which retains the condenser and evaporator but achieves refrigerant compression by other means. The ejector compressor is considered as the heart of the ejector cooling cycle and determines the overall performance and cooling capacity. An ejector can be described as a device which uses the high pressure stream, which can be called 'primary fluid' or 'motive fluid', to drive a second fluid stream, which can be called 'secondary fluid' or 'suction fluid', by direct mixing. The resulting mixture can be discharged at a pressure that lies between the driving pressure and the suction pressure.

A steam ejector refrigerator was first developed by Blance and Parsons around 1901 (Gosney, 1982). To better understand how a typical ejector functions, a description of its operation is given in Fig. 11 (Chunnanod and Aphornratana, 2003). Normally, a steam ejector consists of four principle parts, which are the primary nozzle, mixing chamber, the ejector throat and the subsonic diffuser. The high-pressure primary stream (point P) starts to accelerate as it enters a convergent section of the nozzle and reaches the sonic level at the nozzle throat (i). As the primary stream expands through a divergent section of the nozzle, its speed is further increased and reaches supersonic speed at the exit plane, creating a low-pressure region (ii). This causes the primary stream (the expanded wave) to entrain the secondary fluid in the mixing chamber (S), where the secondary stream is accelerated and completely mixed with the primary stream at point (iii). If the mixed stream is still supersonic at (iii), a shock will occur in the throat (iv), resulting in a subsonic stream at a point determined by the intersection point of Fanno and Rayleigh lines (Alexis and Rogdakis, 2002). The mixed stream is then brought to near zero velocity (*ie*. stagnation condition) as it passes the subsonic diffuser (B).

The primary refrigerant of high pressure and temperature (point 2, see Fig. 12-a & 12-b), evolved from the generator, expands through the primary nozzle of the ejector. This expansion creates a low-pressure region, as explained above, at the primary nozzle exit plane (3) that results in an entrainment of the secondary fluid from the evaporator. The mixed stream is discharged via the diffuser to the condenser (4). After condensation, the refrigerant is pumped back to the boiler, whilst the remainder is expanded through the throttling valve to the evaporator (6). The ejector assists vaporisation of the evaporator refrigerant at low temperature by creating the low-pressure area at the primary nozzle exit.

The main advantages of the ejector refrigeration system are its few moving parts (*ie*. no associated noise or vibration compared to a mechanical compressor), long service life, simple construction, low initial cost and no chemical corrosion. In addition, water can be used as a working fluid. The only limitations of this system are its low COP and cooling capacity.

The first solar-driven ejector air-conditioning system was demonstrated by Sokolov and Hershgal (1993). Refrigerant R-114, which is now banned an environmental grounds, was used in this system. It was shown that for moderate climates, this system could produce hot water, air-conditioning and space heating. The later could be accomplished by passing the solar heat from the collector to the evaporator. More recent work has been carried out using other refrigerants. Better performance was obtained using R-141b (Huang *et.al*., 1998), however the overall COP did not exceed 0.25, since the ejector COP= 0.5 and the solar collector efficiency = 0.5. Arbel and M. Sokolov (2004) replaced R-114 with R-142b as a working fluid. The results indicated that better performance was achieved with R-142b. Particular care must be given when selecting the solar collector and type of refrigerant. Using a higher performance solar collector would increase the generator temperature and consequently the system's efficiency, however this might also adversely affect the properties and chemical stability of the refrigerant.

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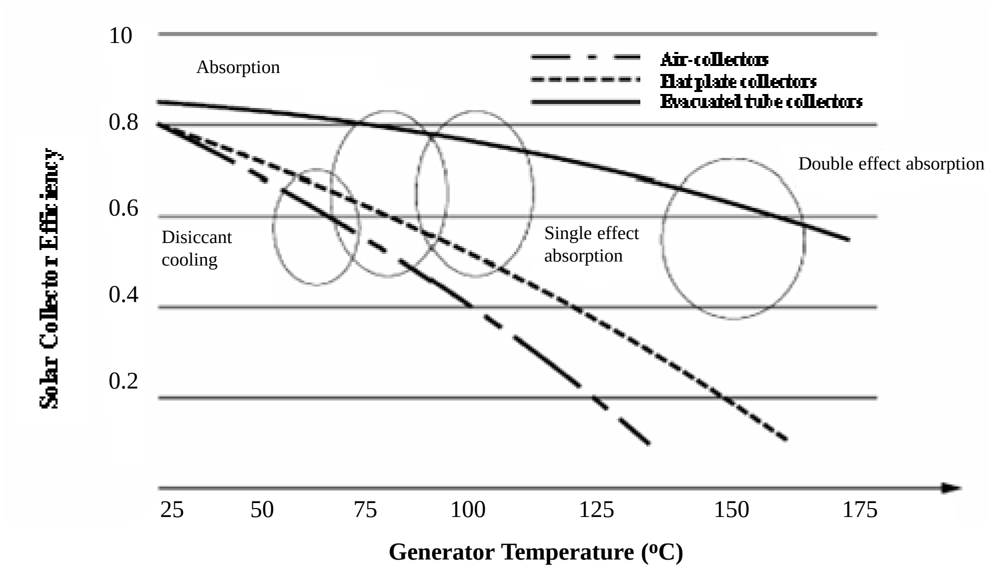

Figure 10. Collector efficiency versus driving heat temperature for various sorption refrigeration systems (Henning, 2000)

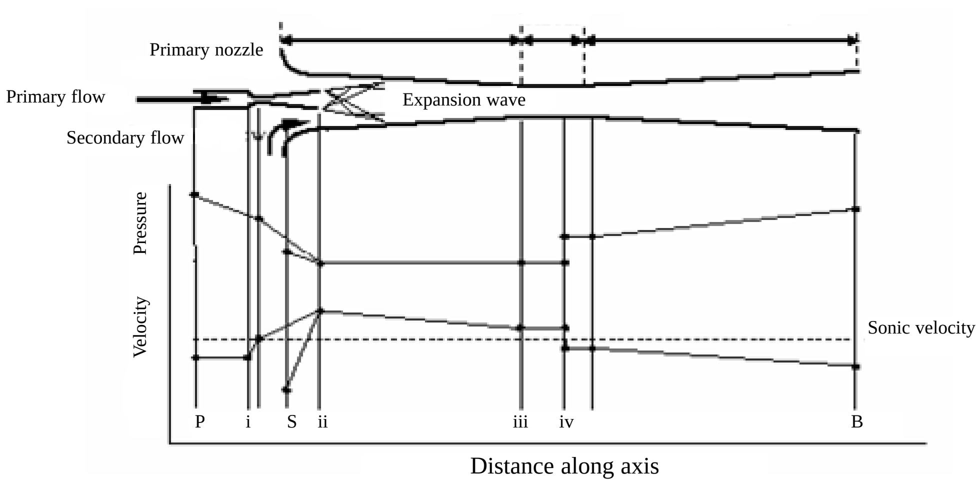

Figure 11. Typical steam ejector and flow characteristic in the ejector (Chunnanod and Aphornratana, 2003)

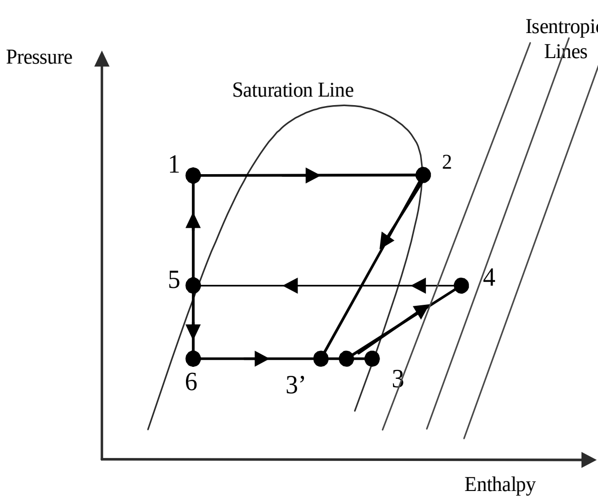

Figure 12-a. P-H diagram of ejector cycle

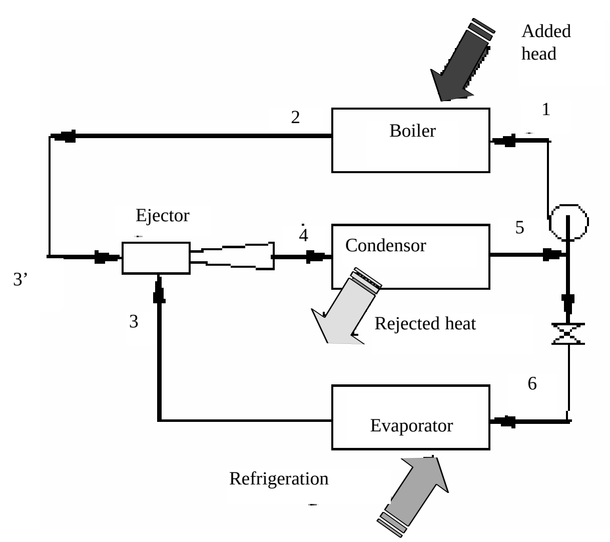

Figure 12-b. Schematic diagram of ejector cycle

A solar powered passive ejector cooling system, which contains no moving parts, has been successfully tested in a UK climate (Nguyen *et al.*, 2001). Some active components were used in the cooling and hot water circuits. A gravity pump was used for refrigerant (water) transfer from the condenser to the boiler and the COP of this design reached 0.32. Research on the solar powered ejector cooling system is still on going. The COP of the system is expected exceed 0.6 when water is used as a refrigerant and a concentrating parabolic trough solar collector is utilized. Generally speaking, the performance of an ejector cooling system is influenced by the working fluid selected, the thermodynamic cycle, and the design of the ejector, especially the compression ratio PDischarge/PEntrainment) (Korres *et al*., 2002).

2.6 Thermoelectric Cooling Cycle

Refrigeration can also be achieved using the thermoelectric effect, which converts electrical energy into a temperature gradient. This phenomenon was discovered by Peltier (1834). Peltier refrigeration occurs when a direct current (DC) is passed from a negative to positive type semiconductor material. The temperature Tc of the interconnecting conductor decreases and heat is absorbed from the environment (cooling effect). This cooling effect occurs, as shown in Fig. 13-a, when electrons pass from a low energy level in the positive type material through the interconnecting conductor to a higher energy level in the n-type material (Riffat, 2003). The potential uses of this system range from cooling of the electronic components, to domestic refrigerators and air conditioners for cooling/heating a room space. Two types of multi-couple thermoelectric devices that are commercially available are shown in Fig. 13-b. These usually consist of a series of p- and n-type bulk semiconductor thermo-elements connected electrically by copper strips and sandwiched between two electrically insulating, and thermally conducting ceramics plates.

Thermoelectric devices offer several distinct advantages over other technologies (Riffat and Ma, 2003):

- Almost maintenance–free due to the absence of the moving parts
- Environmentally friendly, *ie*. contain no CFCs.
- Long lifetime; life testing has shown their capability exceeds 100’000 h of steady state operation.
- They are not position dependent (portable).
- Precise temperature control to within ± 0.1 ^{o}C can be maintained.
- Changing the polarity of the DC power supply causes heat to be pumped in the opposite direction *ie*. a cooler can become a heater.
- They have a wide range of applications, e.g., they could be used as cooler/heaters, power generators or thermal energy sensors.
- A thermoelectric solar-driven air-conditioner can be powered directly by a DC electric source, such as a PV cell.

A thermoelectric solar-driven air conditioner would however be expensive in terms of its capital and operating cost) as it uses a large amount of electricity. Its low COP (0.38-0.45) (Riffat and Qiu, 2004) is an additional factor limiting its application for domestic cooling. Thermoelectric air-conditioners are however very suitable for cooling of small enclosures, such as cars where the power consumption is low. Mei *et al*. (1993) studied a solar-assisted automobile thermoelectric air-conditioner and other studies related to solar thermoelectric refrigerators have been reported. (Dai *et al*., 2003).

3. Coefficient of Performance

Normally, refrigerator/air-conditioner and heat-pump performance is defined by means of coefficient of performance. The coefficient of performance for cooling applications is defined as the amount of cooling delivered by a machine divided by the amount of energy input required to produce the cooling (ASHRAE, 1997).

$$ie.\ COP = \frac{Q_{Evaportor}}{Q_{Compressor}}$$

The best COP is given by a Carnot cycle, which is operating between given temperature conditions. Such a theoretical reversible cycle uses a wet vapour as a working substance, since a superheated vapour cannot fulfill the necessary requirement of the Carnot cycle (*ie*. constant pressure heat supply and heat rejection are made at constant temperature) Figs. 14 -a and 14-b).

The vapour compression cooling cycle is the real (irreversible) cycle based on the Carnot theoretical cycle (refer to Fig. 2). It is worth mentioning that the low COP of the solar-powered cooling cycles compared with the vapour compression cycle does not preclude these cycles, as different power inputs and consequently different definitions of COP are appropriate.

For example, for a vapour-compression cycle, the input power is determined by the amount of mechanical work required to compress the vapour:

$$ie.\ COP = \frac{Q_{Evaportor}}{W_{Compressor}}$$

In a heat-driven cooling cycle, the COP is determined by the amount of heat required (in the generator) and the pump work:

$$ie.\ COP = \frac{Q_{Evaporator}}{Q_{Generator} + W_{Pump}}$$

To make a fair comparison of the COP of two different systems with the same cooling capacity, the energy input needs to be estimated on the same basis. Electricity is the main power driving a conventional air-conditioning system, whereas thermal power and parasitic electric power are used to drive solar-powered systems. Therefore, to compare different systems in terms of thermal and electrical energy inputs, it is reasonable to convert the electric

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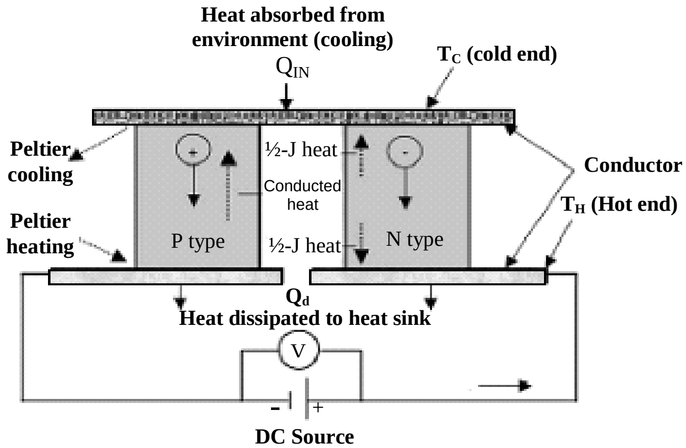

Figure 13-a. Schematic of thermo-electricmodule operation (Cooling mode), Riffat and Ma, 2003)

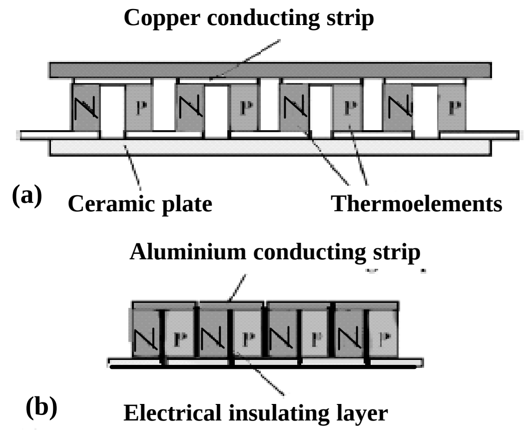

Figure 13-b. Schematic diagram of multicouple thermoelectric modulus
(a) With large inter-thermo-element separation
(b) With small inter-thermo-element separation

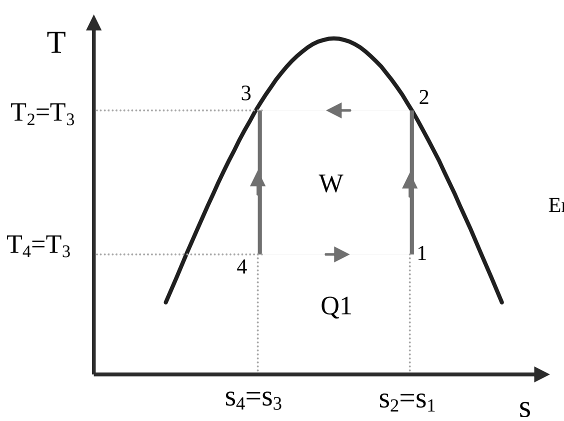

Figure 14-a. Carnot cycle, T-s diagram

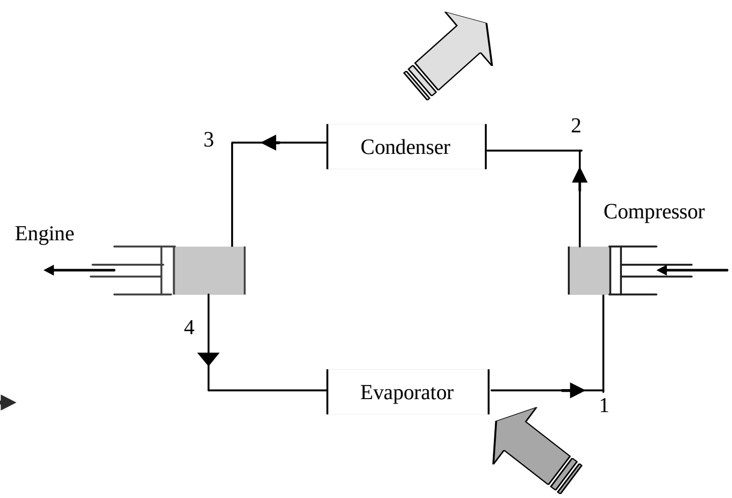

Figure 14-b. Carnot cycle schematic diagram

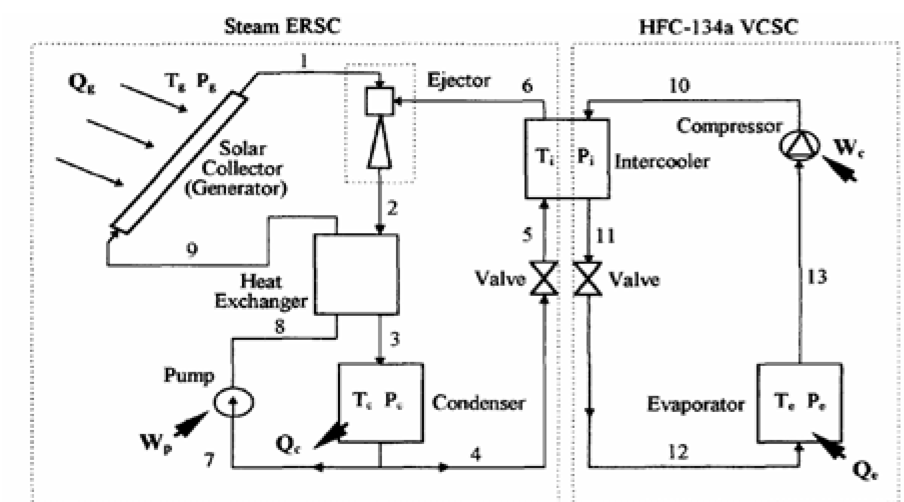

Figure 15. Schematic diagram of a solar-powered combined ejector-vapour compression ccle (Sun, 1997)

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power back into heat to provide an estimation of the actual COP, losses in electric power consumption and calculate the energy saving potential of solar-driven systems on the basis of heat input.

Some research effort has been directed to combine two or more refrigeration cycles to improve the coefficient of performance (COP) of the system. Sozen, *et al*. (2003) investigated performance prediction of a solar driven ejector-absorption refrigeration system (EARS) using fuzzy logic. The maximum calculated COP of the system was 0.62, 0.69, and 0.79 at evaporator temperatures of -10, 0, and +10 C, respectively with a deviation of 1.2% or less.

Adopted direction of a combination of two cooling cycles might be an effective solution to overcome the limitations of many cooling cycles. This combination phenomenon has been applied to a mechanical vapour compression cycle combined with a solar powered ejector cycle (Sun, 1997). The combined cycle, as shown in Fig.15, brings together the advantages and eliminates the disadvantages of the two conventional cycles.

The thermodynamic analysis shows that this combined cycle offers the following advantages:

- Improvement of system efficiency by more than 50% over the vapour compression cycle.
- Environment-friendly system, as water is used in the ejector cycle and HFC-134a in the vapour compression cycle, *ie*. ODP = 0. Also the energy saving of more than 50% means that less electricity is used in the system, and consequently less CO_2 is released to the atmosphere by the combustion of fossil fuels.
- The main additional cost for the combined cycle is in the solar panels. This would be offset by the saving in the electrical energy.

Elsafty and Al-Daini (2001) has presented an economic comparison between a solar-powered vapour absorption system (for both a single and double effect system) and a conventional vapour compression system, (Elsafty and Daini, 2001). The cost analysis covered the initial and operating costs of each system and considered the interrelationship between economic and thermodynamic aspects, such as the dependence of operating cost on the surrounding climate conditions. The results showed that the double-effect vapour absorption system was the preferred option for its minimum present worth value, as well as the equivalent annual cost.

Mistuhiro *et al*., (2001) discussed the feasibility of a vapour compression/absorption hybrid refrigeration cycle for energy saving and utilization of waste heat. The cycle employed propane as a natural refrigerant and refrigeration oil as an absorbent. The experimental results were in close agreement with the mathematical calculation, which showed that the hybrid cycle using waste heat (Fig. 16) had the potential to achieve a higher performance (COP) than the vapour compression cycle.

A novel solar-powered adsorption-ejection refrigeration system has been studied (Li, *et al*. 2002) in order to overcome the intermittence of adsorption refrigeration. The ejection cycle operates during the day, while the adsorption cycle operates at night time.

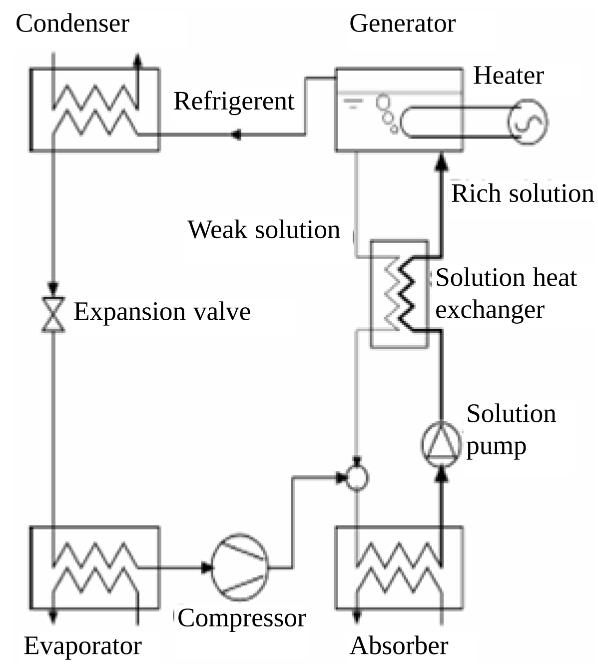

Figure 16. Schematic diagram of a vapour compression/absorption hybrid cycle. The absorption unit is connected to the compressor exit in series (Mistuhiro *et al*., 2001)

4. Conclusions

The following conclusions can be drawn from this study:

- Several technologies for solar powered air-conditioning have been described. In comparison with conventional vapour-compression systems, these systems usually have a higher initial cost, and it is this economic barrier, rather than technical difficulties, which has limited the emergence of these technologies. As the collectors are normally the most expensive component of a solar-operated system, it would be cost effective to use them for more than one purpose, *eg*. collectors used in a water-heating system during the winter, could be utilized to power an air-conditioning system during the summer.
- It is more realistic to base a comparison of the COP of the vapour compression system with a solar-driven systems on primary energy input rather than shaft work input. The reason for the high values of COP quoted for vapour compression cycles is then clear, as no account for the heat input in power generation has been made for typical analyses of vapour compression cycles.
- The use of combined cooling cycles could be an effective solution to overcome the limitations of many cooling cycles, e.g., the low COP. The high capital cost of solar systems would fall as mass production techniques evolve in line with market penetration.

- Combined cooling cycles could also be used for energy saving and reduced CO_2 emission.
- Problems of the GWP and ODP of many refrigerants used in vapour-compression systems could be eliminated/reduced by the use of solar-powered or combined cooling cycles.

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