CHAPTER 5

REFRIGERATION USING SOLAR ENERGY

Refrigeration is one application of solar energy where the demand matches with the availability of solar radiation. Because of this advantage and the increasing cost and uncertainty of conventional fuels, serious efforts are underway all over the world to develop technically and economically viable solar cooling systems. Air conditioning for achieving comfort conditions for living, refrigeration for storage of perishable food products, essential drugs and vaccines are the main areas in which solar energy can be employed.

Refrigeration using solar energy can be achieved through the following means :

- Vapour Compression Systems (VCS)
- Vapour Absorption Systems (VAS)
- Vapour Jet Systems (VJS)
- Thermo-electric cooling systems
- Adsorption refrigeration systems

5.1 VAPOUR COMPRESSION SYSTEMS (VCS)

The vapour compression refrigeration system consists of a compressor, condenser, expansion valve and evaporator. There are two pressure levels in the system - high pressure prevailing in the condenser and low pressure in the evaporator. Fig. 5.1 shows the schematic diagram of a VCS system and also shows the high and low pressure sides. The high pressure refrigerant leaving the compressor is

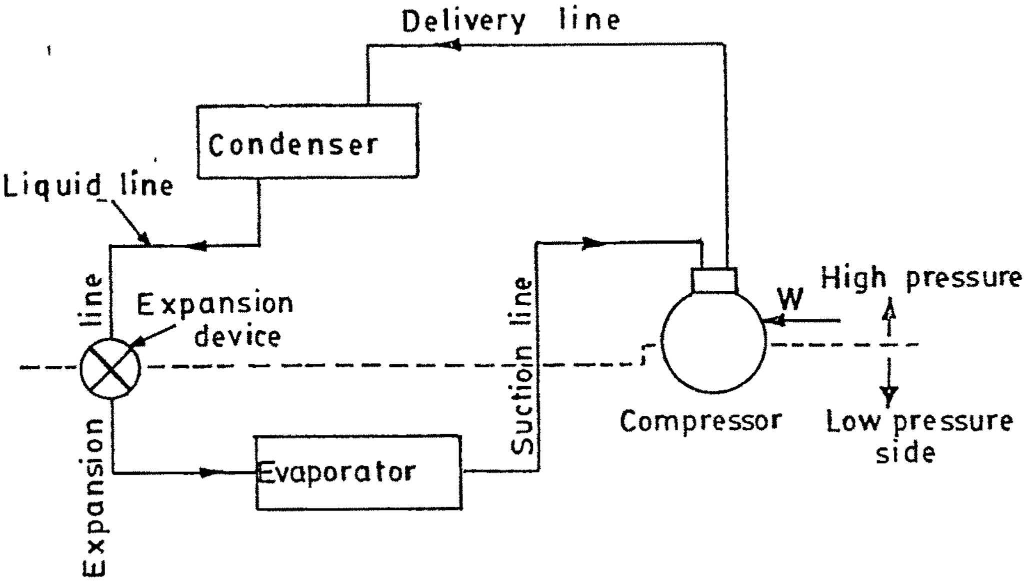

Fig. 5·1 . Schematic diagram of vapour compression system

condensed in the condenser. The condensate under high pressure enters the evaporator and evaporates by absorbing heat from the surrounding. The low pressure refrigerant then flows to the compressor and the process is repeated. The expansion valve is used to separate the high and low pressure sides.

The conventional VCS systems can be operated either by using heat engines or solar cell based electric motors. The heat engine which can be operated using solar energy will operate the compressor of the VCS. For such a system, solar energy collectors, working fluid, circulation pump and condenser are essential. Such systems of small scale have not yet become economically feasible.

Using solar cells to operate an electric motor which in turn operates the compressor is an attractive and convenient but expensive option[1].. Many such refrigerators are in use in India on a demonstration level but due to their very high cost these are unlikely to become popular.

Another important drawback of vapour compression systems is that they use Chloro FluoroCarbons (CFCs) as refrigerant. CFCs have been proved to cause thinning of the protective ozone layer surrounding the earth leading to the entry of dangerous Ultra Violet (UV) radiation into the earth's surface. Hence any further development based on CFC is not in the interest of the eco system. Efforts are already on to phase out technologies using such harmful chemicals by developing alternative methods. In accordance with the Montreal Protocol, all CFCs must be banned as of 1 January 1996. On 1st January 1995, European Refrigerator manufacturers were to stop working with CFC according to the EEC regulations. Developing countries have a ten year grace period and need not phase out these before 1 January 1999[2].

5.2 VAPOUR ABSORPTION SYSTEMS (VAS)

The VAS being a heat operated system requiring very little mechanical energy compared to VCS is more suitable for refrigeration using solar energy. Intermittent cycle and continuous cycle VAS systems have been investigated. Intermittent cycle based systems use solar energy available during the day time to liberate refrigerant from the absorbent. In the night the refrigerant evaporates from the evaporator producing cooling. Such systems were developed as early as in 1957[3] and the first reported work in India was in 1961 [4,5]. The major advantages of these systems are the simplicity of design and construction and the elimination of any refrigeration pump. These systems do not provide continuous cooling and are physically large due to their low Coefficient of Performance (COP).

Continuous cycle VAS :

The popular systems are the Aqua-Ammonia and Lithium Bromide-Water on which considerable amount of work has already been done. In the continuous systems, show in Fig. 5.2, the generator, condenser, evaporator and absorber are

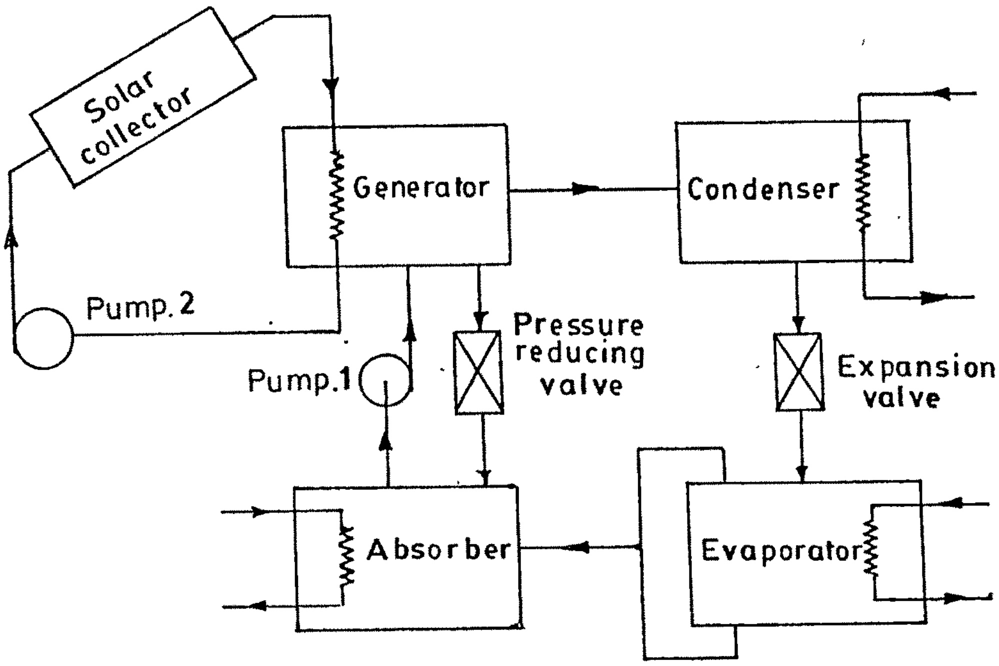

Fig. 5·2 Vapour absorption refrigeration system .

separate units. Heat generated in the solar collector is used in the generatior to increase the pressure and temperature of the refrigerant. The high temperature refrigerant gas gets condensed in the condenser. The high pressure condensate then evaporates in the evaporator which produces the cooling. The low pressure vapour leaving the evaporator gets adsorbed in the adsorbent present in the absorber. A solution pump is used to pump the refrigerant from the low pressure absorber region to the high pressure generator region. These systems have many advantages.

a) temperatures below zero degree C can be obtained.
b) can be used for air conditioning, refrigeration, and cold storage.
c) Systems are compact and are easy to integrate with solar applications.

Considerable amount of work was done on LiBr-H_2O pair in the USA, Australia and Japan[6,7,8]. Commercial air conditioning systems are now available in USA and Japan. Similar systems are also available in India.

The pioneering work on solar operated NH_3-H_2O systems was done by Farber[9] at the University of Florida. Many researchers in India have also worked on similar systems and many field installations have already been undertaken in the Country [10].

The Sardar Patel Renewable Energy Research Institute at Vallabh Vidyanagar, Gujarat, India has designed and installed a 3RT cold storage working on solar energy and wood fired boiler for sub zero operating temperatures[11]. Steam at 150 degree C produced in the solar collectors or biomass boiler was used in the generator to librate ammonia from the aqua-ammonia solution. Rectifier and dephlagmeter were used to condense any water vapour present in the ammonia vapour. The high pressure ammonia vapour was then condensed in the condenser. The condensate was then introduced into the evaporator for evaporation and thus generate cooling. The low pressure ammonia vapour was allowed into the absorber to form aqua-ammonia solution. A cooling tower was used to cool the water circulated in the absorber, condenser and dephlagmeter. This system was designed to produce -18 degree C in the cold room and the system was tested for fish storage. The system performance was monitored for over one year and the results were satisfactory.

In a solar powered VAS, the generator temperature attainable is much lower than that of the commercially available oil or gas fired systems resulting in lower COP. Also these systems are economical and technically viable only in large capacities often of the order of 50 RT and above.

5.3 VAPOUR JET SYSTEMS (VJS)

Utilization of solar energy for production of refrigeration using vapour jet system seems to have good application potential.

Fig. 5.3 shows the basic components of a VJS powered by solar energy. An ejector and a liquid circulation pump function like the compressor of a VCS. Similar to VAS, the vapour jet system is also a heat operated one. Hence it presents immense possibility of direct adoption to solar energy application. The system has the advantages of simplicity, absence of moving parts and little maintenance requirements.

VJS with water as the refrigerant is suitable for high temperature energy source but water limits the level of refrigeration temperatures attainable with the system. Hence operating the system with working fluids which vapourises and operate efficiently at temperature levels possible with simple solar energy devices is a potential option which needs continued investigation.

The main drawback of the system is its low efficiency resulting from the high irreversible nature of the ejector. Many investigators in India and abroad conducted studies on application of VJS for vapours other than steam[12,13,14] with mixed results.

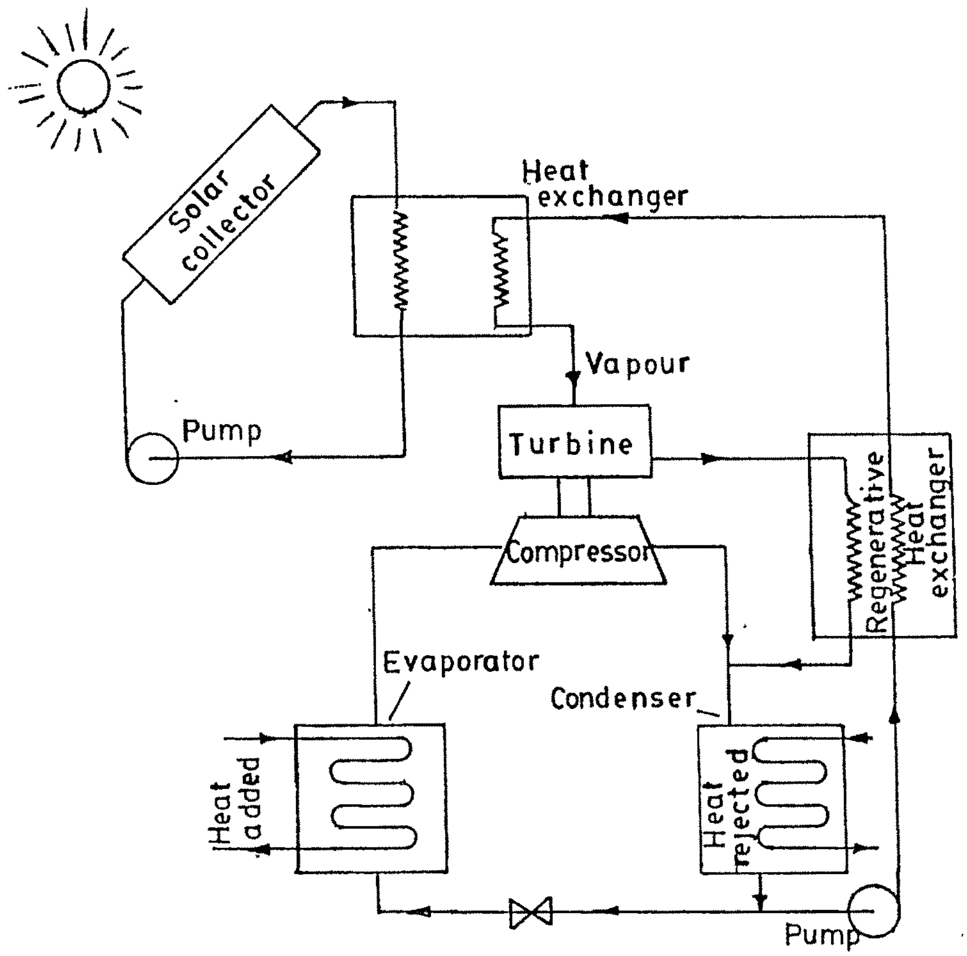

Fig. 5·3 Vapour jet system powered by solar energy.

5.4 THERMO-ELECTRIC COOLING SYSTEMS

Thermoelectric cooling is a potential option for refrigeration that uses electrical energy directly without converting it into mechanical form to obtain cooling. The principle of thermoelectric cooling is based on reversible thermoelectric effect. Since there are no mechanical parts in the system, it is free from wear and tear problems and noise.

The thermoelectric effect is the generation of electric current in a closed circuit of dissimilar conductors maintained at different junction temperatures. Peltier in 1834 observed that if a current is passed through such a circuit, absorption or rejection of thermal energy occurs at the junctions. This effect known as Peltier effect is responsible for thermoelectric cooling systems. The overall efficiency of the thermoelectric refrigeration system is low, but the simplicity of the device is an attractive advantage over other alternatives.

In a solar thermoelectric refrigeration system a combination of a thermoelectric heat engine and refrigerator is used. The heat engine draws its heat from solar energy and converts it into electrical energy. The electricity thus generated is used for the operation of the thermoelectric refrigerator.

5.5 ADSORPTION REFRIGERATION SYSTEMS

Adsorption refrigeration systems based on vapour adsorption by liquid or solid dessiccants is another area which offers considerable potential for solar energy applications. Two types of systems called Open Cycle and Closed Cycle have been investigated. Open cycle is usually used for air conditioning applications whereas closed cycle is preferred for refrigeration applications.

5.5.1 Open Cycle Systems :

Figure 5.4 shows the principle of open cycle adsorption

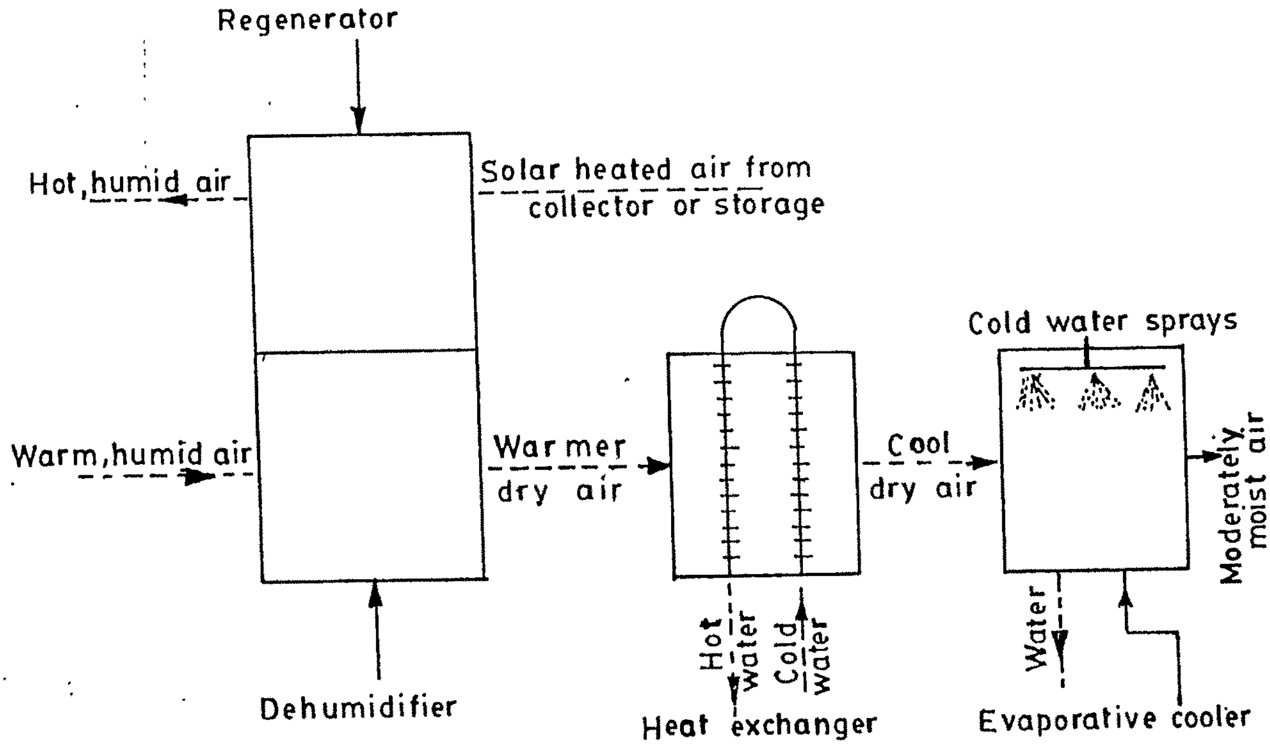

Fig. 5.4 Open cycle adsorbent cooling system.

cooling system. Warm humid air from the ambient is passed through the desiccant which adsorbs the moisture. As adsorption results in heating of the air, a heat exchanger is used to cool the warm air before passing it through the evaporative cooling arrangement. The solid desiccants used in such systems are silica gel and molecular sieves and the popular liquid desiccants are triethylene glycol and lithium chloride. Liquid desiccants are favoured over solid ones due to reduced pressure drop and better heat and mass transfer from liquid surface[15,16,17]. Such systems provide a COP of about 0.5. Open cycle systems can be used only for space cooling applications.

5.5.2 Closed Cycle Systems :

Refrigeration and ice generation applications are possible through closed cycle systems and hence these are drawing considerable attention.

The systems are usually intermittent in nature. An adsorbent-refrigerant pair with matching properties is used in these systems. The refrigeration effect is produced during the night time when the adsorbent is cool and is capable of adsorbing the refrigerant. Cooling is produced when the refrigerant evaporates and gets adsorbed by the adsorbent.

The present investigation mainly deals with development of a solid adsorption closed cycle solar refrigerator for vaccine storage in rural areas using a synthetic zeolite as the adsorbent.

Of the various adsorbent-refrigerant combinations possible, the molecular sieves - water pair is found to have vast potential due to their unusual sorption properties. A small refrigerator, independent of conventional fuels and without major maintenance requirements will perfectly fit into the existing and well known need for refrigeration in the country. Rural hospitals and health centres situated in areas without reliable electric power supply often face difficulties in storing essential medicines and vaccines due to the lack of refrigeration facility. The zeolite-water adsorption refrigerator is a device that can be put into real applications in rural India.

Zeolite-water adsorption refrigerator does not require any conventional energy source for its operation. Also it does not have any moving parts requiring frequent maintenance. The system is capable of producing temperatures of the order of 3 to 8 degree C which is sufficient for many applications like storage of vaccines and other essential items. The refrigerator operates under vacuum and maintaining vacuum in the system for long durations require careful operation.

Studies elsewhere have shown that natural zeolites are better suited for solar refrigeration applications due to the higher sorption properties. In Indian, natural zeolites are mainly concentrated in the Deccan Traps in Western Maharashtra. Due to the difficulty in obtaining sufficient quantity of these in a pure form, synthetic zeolites were used in the current study.

Synthetic zeolite, molecular Sieve 13X, manufactured by Indian Petrochemicals Corporation Ltd. was used in this study. The 13X has the largest pore diameter of 10 angstroms which provides it very high adsorption capacity for a variety of molecules like water, carbon dioxide, hydrogen sulphide and freones. As the latent heat of vaporization of water is one of the highest among the known refrigerants, 13X-Water combination requires the smallest amount of zeolite.

Zeolites also have the unique property, which is important for solar applications, that their adsorption isotherms have an extremely nonlinear pressure dependence. Fig. 5.5 gives the typical isotherms for the adsorption of water vapour on

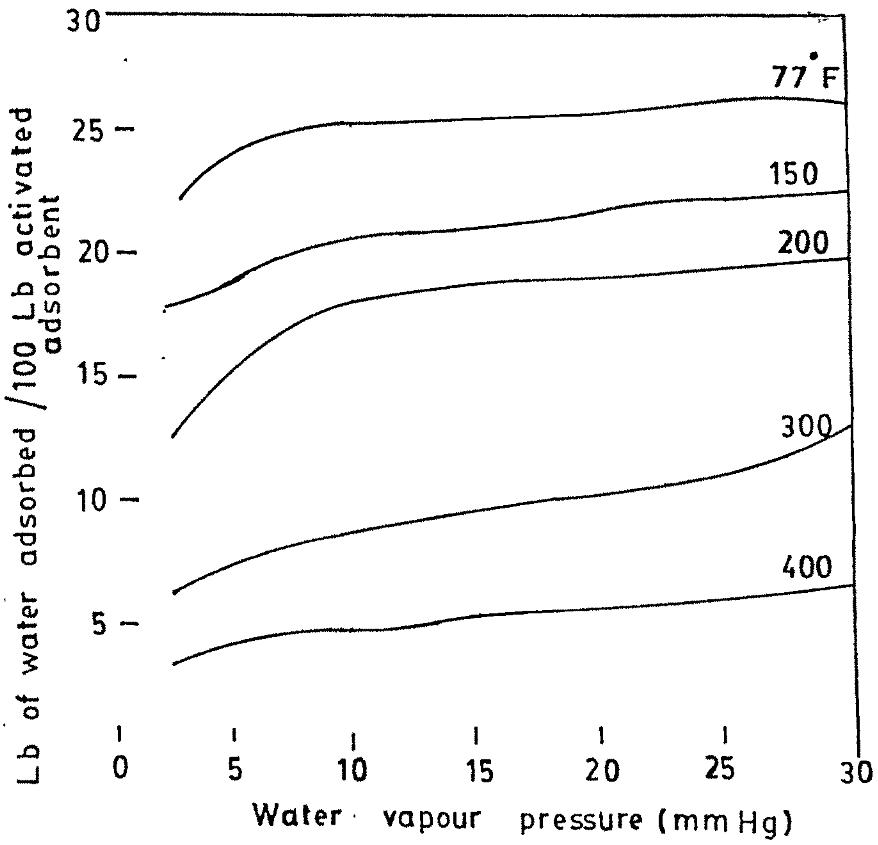

Fig . 5·5 Adsorption isotherms for water vapor on zeolite. Source : D I Tchernev

zeolite. The nonlinearity of the amount of water adsorbed as a function of partial pressure is obvious. The isotherms saturate at low partial pressures, after which the amount adsorbed is almost independent of pressure. Therefore when zeolite is at ambient temperature it can adsorb large quantities of water vapour even at low partial pressures. When zeolite is heated it desorbs most of the water vapour even at high partial pressures. Thus the difference in adsorbed gas between the high and low operating temperature stages are large. This makes it possible to achieve higher efficiencies under typical solar conditions by zeolite based system than systems based on other adsorbents.

The pioneering work on vapour adsorption-desorption systems was done by Tchernev[18,19] in USA which was followed up by other researchers like Grenier, Dupont, Guilleminot, and Meunier[20-26] in France. Some contributions by Sakoda & Suzuki[27,28], Jian Wn. & Xiaole Li[29], Phadke[30], & Gandhi[31] have also been reported in the literature.

The use of two natural zeolites clinoptilotite (Zeosorb 3.5 A) and Chabazite/erionite (Zeosorb 5.0 A) for solar cooling was studied and demonstrated by Tchrenev[18,19]. Systems which could provide domestic hot water and space heating with overall efficiencies above 75% and space cooling with overall efficiency of above 50% were demonstrated. Test panels of 1 and 2 sq.ft were constructed with metals like brass, copper, aluminium and tin-plated steel. The systems were developed and tested under simulated as well as outdoor conditions. In these tests the chabazite rich 5.0 A showed superior performance achieving an overall engineering efficiency of 42%. Larger systems consisting of about 1 sq.m. collector were also tested. It was demonstrated that such systems were capable of providing space heating and cooling as well as refrigeration and ice making with remarkable efficiency.

Though the performance of natural zeolite was observed to be superior than that of synthetic material, due to the difficulty in obtaining and cleaning natural zeolite, synthetic zeolites were also used to develop refrigerator.

Considerable amount of work has been done in France on synthetic zeolite-water cycle for refrigeration and space cooling[20-26]. Molecular Sieves 13X manufactured by Union Carbide Corporation was used in these work. Models of different capacities were developed and tested. The results indicated the feasibility of producing refrigeration through the solid adsorption cycle.

A laboratory scale study to obtain quantitative data on an adsorption cycle was carried out by Sakoda et all[27,28] in the University of Tokyo. Silica-gel and water were used as the adsorbent - adsorbate combination. An infrared lamp was employed to heat silica gel. The amount of adsorption and desorption was measured at different temperatures. A theoretical model of the system was also developed to interpret the experimental results quantitatively.

Wu Jian et al. in China have also done theoretical as well as experimental work on zeolite refrigerators[29].

Experiments were conducted to predict the refrigeration capacity, the regeneration temperature, the coefficient of performance and energy efficiency of the Zeolite 13X-H2O intermittent system. An experimental setup was made using 1.5 kg of zeolite 13X and 0.5 kg of water. A hot air blower was used to heat zeolite. The performance of the cycle was studied at various temperatures ranging from 80 degree C to 120 degree C. It was observed that the difference between the theorotical and actual experimental refrigeration capacity was not more than 17%. The scientists observed that this system could be very useful in the recovery of waste heat from the exhaust of diesel engines. Such a system was reported to be under development.

In India the work on zeolite refrigerators was initiated in Pune University[30]. Naturally occuring zeolite in western parts of Maharashtra were identified and used to develop experimental models of solar adsorption refrigeration system. The major component of the zeolite was clinoptilotite. About 4-5 kg of the zeolite was loaded in the solar collector of 0.1 sq.m. area. During the experiments, it was observed that approximately 200 to 300 cc of water was desorbed from the zeolite on an average sunny day. In the night, this water was adsorbed by the zeolite producing cooling in the evaporator. The work was limited to laboratory level experiments.

The Central Salt and Marine Chemicals Research Institute in Bhavanagar also worked on this problem[31]. Efforts were made to develop an adsorption refrigeration system using Molecular sieves 13X. The collector was of G I sheet with 0.19 sq.m. of area. The box type collector was filled with 4 kg of 13X. Pipe matrix was provided in the collector for vapour flow. The other main components of the system were an air cooled condenser and an M.S. evaporator of 2 litres capacity.

Experiments were conducted for many days. The maximum temperature at the collector top was 140 degree C and the bottom was about 20 degree C lower. The minimum evaporator temperature was about 2 degree C and the average adsorption-desorption rate was about 100 cc per cycle. The work done at Bhavanagar was also limited to laboratory scale studies.

5.5.3 Operating Principle of Zeolite Refrigerator :

The adsorption - desorption property of zeolite at different temperatures is utilized to produce cooling in a zeolite-water refrigerator. The working principle of the system is illustrated in Fig. 5.6. The zeolite is filled in the solar collector which gets heated in the day time. When the zeolite becomes hot, water vapor starts to desorb from the zeolite and goes to the condenser. The partial pressure starts to rise and when it reaches the value corresponding to the condenser temperature, it starts to condense. The heat of condensation is lost to the atmosphere and the water is collected in the storage tank. This process continues for the entire day. During the night the zeolite is cooled to ambient temperature and the zeolite becomes ready to adsorb water vapour. The water collected during the day cycle is then transfered to the evaporator. The water

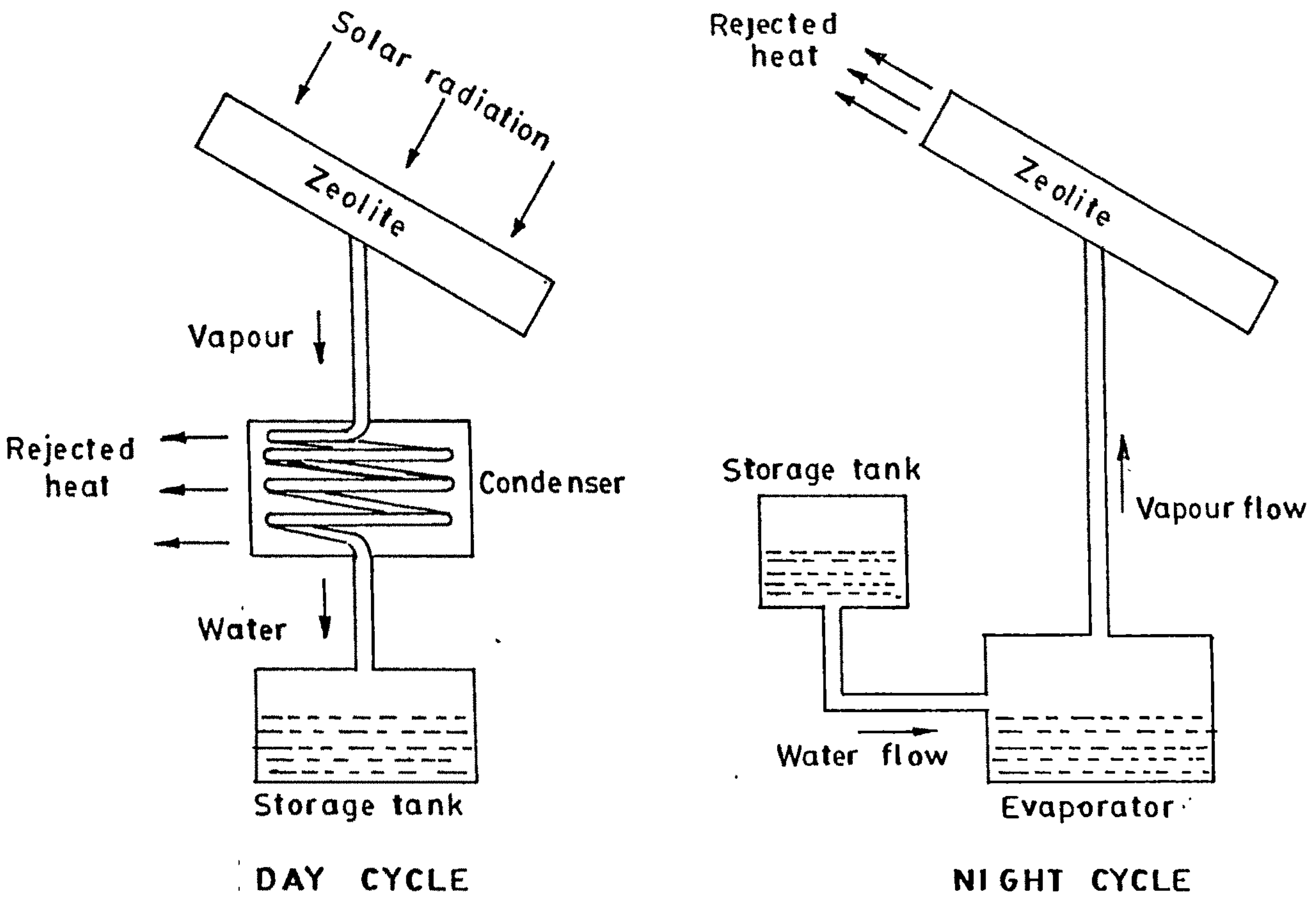

Fig. 5·6 Working principle of the Zeolite – water refrigerator system.

takes heat from the surroundings and is converted to water vapour. The zeolite adsorbs the water vapour thereby maintaining low partial pressure inside the evaporator. This results in continuous evaporation of water. If the evaporator is placed inside an insulated box, the temperature of the box can be lowered through evaporative cooling. A well designed system can produce ice inside the evaporator if extra water is kept in the evaporator. At the end of the night cycle, the zeolite becomes saturated with water vapour and the adsorption cycle comes to an end. The heat of adsorption released during adsorption of water by the zeolite in the night cycle is also lost to the atmosphere.

The zeolite refrigerator works only in an air free atmosphere and due to this the whole system has to be evacuated and maintained leak proof.

REFERENCES :

1. Tata BP Solar India, Business India, 92, October 26 - November 8, 1992.

2. Technet News, 932, (1993), E, P1, WHO.

3. Kaushik S.C., Solar Refrigeration and Space Conditioning, Divyajyoti Prakashan, Jodhpur, 1989.

4. Chinnappa, J.C.V., 'Experimental study of the intermittent vapour absorption refrigeration cycle employing the refrigerant absorbent systems of ammonia-water and ammonia-lithium nitrate', Solar Energy, Vol. 5, pp. 1-18, 1961.

5. Chinnappa, J.C.V., 'Performance of an intermittent refrigeration operated by a flat plate collector, Solar Energy, Vol. 6, pp. 143-150, 1962.

6. Arkla Industries, Inc., Evanville, Indiana, Solaire 36, Models WF-36 and WEB-3, Application Manual, 1978.

7. Sheridan, N.R., 'Performance of the Birsbane Solar House', Proc. ISES Conference, Melborerni, Australia, 1970.

8. Yazaki Corporation, Yazaki Solar Aid Conditioning systems Equipment', (Pamphlet), Tokyo, Japan.

9. Farber, E.A., 'Design and performance of a compart solar refrigeration system', Proc. ISES Conference, Melbourne, Australia, 1970.

10. State of Art Report on Solar Refrigeration and Air Conditioning, Rao, C.S.; Singhal, A.K.; Philip, S.K., Sardar Patel Renewable Energy Research Institute, 1989-90.

11. Singhal, A.K.; Philip S.K.; Patel S.R.; and Rao, C.S., Performance evaluation of 3 ton solar assisted hybrid refrigeration plant for sub-zero operating temperatures, International Journal of Energy Research, Vol. 14, 293-303, 1990.

12. Mizrahi, J., et al, 'Ejector refrigeration for low temperature energy sources', Bull. Res. Council of Israel, Vol. 66, pp. 1-8, 1987.

13. Chon S.K., and Bong T.Y., 'Tropical operations of a heat driven freon jet refrigeration system', Solar World Congress, Perth, pp. 114-119, 1983.

14. Balasubrahmanian, R.; Srinivasa Murthy S., and Krishna Murthy M.V., 'Solar-driven vapour jet refrigeration system : a comparative thermo-dynamic study, Proc. Solar Cooling Workshop, IIT, Madras, 1984.

15. Dunkle, R.V., 'A method of solar air conditioning' Mech. and Chem. Engr. Trans., Aistralia, MCI [1], 73-78, 1965.

16. Rush W.F., 'Development of a Noval Solar heating and cooling device', Second symposium of Engineer El Salvador, 1979.

17. Nelson J.S.; Beakman W.A.; Mitchell J.W.; Duffie, J.A.; and Close D.J., 'Simulation of the open cycle desiccant cooling systems', Solar Energy 21(4), 273-278, 1978.

18. Tchernev D.I., 'Solar Energy Application of Natural Zeolites' in Natural Zeolites, Occurances, properties, Use', Eds L.B. Sand and F.A.Mumption, pergamon press, Oxford (1987).

19. Tchernev D.I., 'The Use of Zeolites for Solar Cooling', The Zeopower Company, 75, Middlesex Avenue, Natick, Massachsetts 01760, USA.

20. Meunier F & Mischler B., 'Solar Cooling Through Cycles Using Microporous Solid Absorbents', In Sun II, Proc. Int. Congr of the ISES, Atlanta(1979) p. 676.

21. Guilleminot J.J., Meunier F., 'Experimental Results on the Adaptation of the Intermittent Zeolite 13X - Water Cycle

to - a solar powered individual refrigerator - a twelve cubic meters solar powered food storage unit. ISES, Solar World Congress, Brighton, (1981).

22. Brandon et al, 'Solar Cooling Through Zeolite 13X - Water Pseudo Continuous Cycles', ISES Solar World Congress, Brighton, 1981.

23. Monnier J.B., Dupont M., 'Zeolite - Water Close Cycle Solar Refrigeration, Numerical Optimisation and Field Testing'.

24. Meunier F. et al, 'On the Use of Zeolites 13X - Water Intermittent Cycle for the Application to Solar Climatization', Atlanda(1979), p. 739.

25. Grenier ph, Guilleminot J.J. et al, 'Experimental Results on a 12 m3 Solar Powered Cold Store using the Intermittent Zeolite 13X-H2O cycle. A Paraitre a I'ASME.

26. Grenier ph. & Pons. M., 'Experimental and Theoretical Results on the Use of an Activated Carbon CH3OH Intermittent Cycle for the Application to a Solar Powered Ice Maker', Solar World Congress, Ed by Szololay S.V., Vol.1, Pergamon' press pp. 500-506(1984).

27. Sakoda, A & Suzuki M., 'Fundamental Study on Solar Powered Adsorption Cooling System', Journal of Chemical Engineering of Japan, Vol. 17 No. 1 (1984).

28. Sakoda A. & Suzuki M., 'Simultaeous Transport of Heat and Adsorbate in Closed type Adsorption Cooling System Utilizing Solar Heat', Journal of Solar Energy Engineering, Vol. 108 (1986).

29. Wu Jian, Li Xiaole, 'The Prediction of Refrigeration Characteristics of Molecular Sieve Adsorption Refrigeration System', Proc. Aust Inst. Energy National Conference, Melbourne 1985.

30. Phadke A.V., 'Natural Occurance of Clinoptiolite from Western Maharashtra. Its utilization in Refrigeration using Solar Energy', Paper presented at Seminar on Research and Development for Planned Utilization of Mineral Resources, New Delhi (1982).

31. Gandhi M.R. et al, 'Experimental Performance of Adsorption Refrigeration System Using Molecular Sieves Type 13X and Water Proceedings of the National Solar Energy Convention (1986).