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A review on Solar Powered Refrigeration and the Various Cooling Thermal Energy Storage (CTES) Systems

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Abstract

In this paper, a review has been conducted on various types of methods which are available for utilizing solar energy for refrigeration purposes. Solar refrigeration methods such as Solar Electric Method, Solar Mechanical Method and Solar Thermal Methods have been discussed. In solar thermal methods, various methods like Desiccant Refrigeration, Absorption Refrigeration and Adsorption Refrigeration has been discussed. All the methods have been assesed economically and environmentally and their operating characteristics have been compared to establish the best possible method for solar refrigeration. Also, the various available technologies for Cooling Thermal Energy Storage (CTES) have been discussed in this paper. Methods like Chilled Water Storage (CWS) and Ice Thermal Storage (ITS) have been compared and their advantages and disadvantages have been discussed. The results of the review reveal Solar Electric Method as the most promising method for solar refrigeration over the other methods. As far as CTES systems are concerned, ITS has advantage over other methods based on storage volume capability, but it has a comparatively lower COP than other available techniques.

Keywords: Solar powered refrigeration, Solar Electric Method, Solar Mechanical Method, Solar Thermal Method, CTES system, Chilled Water Storage (CWS) system, ice TES systems, etc.

Introduction

A solar-powered refrigerator is a refrigerator which runs on electricity provided by solar energy. Solar-powered refrigerator are able to keep perishable goods such as meat and dairy cool in hot climates, and are used to keep much needed vaccines at their appropriate temperature to avoid spoilage. Solar-powered refrigerators may be most commonly used in the developing world to help mitigate poverty and climate change. In developed countries, plug-in refrigerators with backup generators store vaccines safely, but in developing countries, where electricity supplies can be unreliable, alternative refrigeration technologies are required. Solar fridges were introduced in the developing world to cut down on the use of kerosene or gas-powered absorption refrigerated coolers which are the most common alternatives. They are used for both vaccine storage and household applications in areas without reliable electrical supply because they have poor or no grid electricity at all. They burn a liter of kerosene per day therefore requiring a constant supply of fuel which is costly and smelly, and are responsible for the production of large amounts of carbon dioxide. They can also be difficult to adjust which can result in the freezing of medicine. The use of Kerosene as a fuel is now widely discouraged for three reasons: Recurrent cost of fuel, difficulty of maintaining accurate temperature and risk of causing fires.

There are three methods by which solar energy can be utilized for refrigeration purposes. They are as follows- Solar Electric Method, Solar Mechanical Method and Solar Thermal Method.

Solar Electric Method

In Solar Electric Method, the solar energy is directly converted to DC current by an array of solar cells known as Photovoltaic (PV) panel. Photovoltaic Cells are nothing but semiconductors which allow direct conversion of solar energy to direct current. A part of this current is stored by lead acid battery while the rest is utilized in driving the compressor of the refrigerator. This DC current can be either used to run a DC motor coupled to compressor or an inverter can be used to convert this DC current to AC current for running the compressor. A solar charge controller consisting of capacitor, sensors etc. may be required to stabilize and smoothen the current. (**refer fig. 1**)

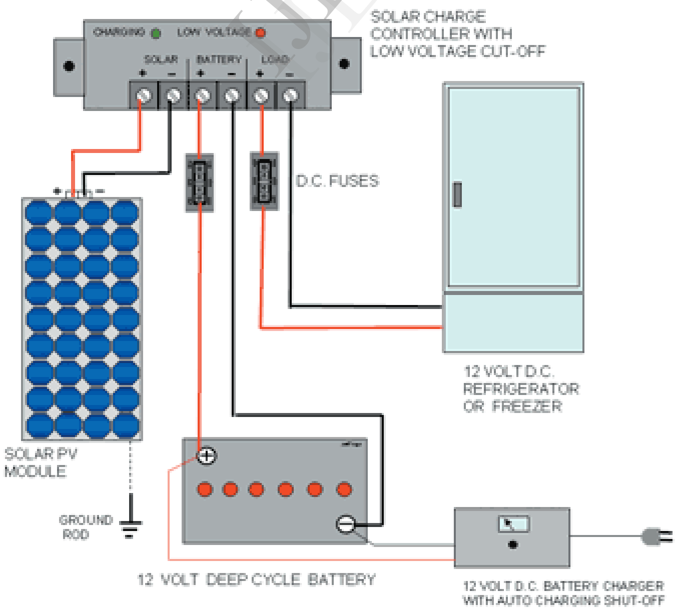

Fig. 1- A typical Solar PV system

A normal Solar PV system includes different components that should be selected according to the system type, site location and applications. The major components for solar PV system are solar charge controller, inverter, battery bank, auxiliary energy sources and loads (appliances).

- PV module – converts sunlight into DC electricity.
- Solar charge controller – regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life.
- Inverter – converts DC output of PV panels or wind turbine into a clean AC current for AC appliances or fed back into grid line.
- Battery – stores energy for supplying to electrical appliances when there is a demand.
- Load – is electrical appliances that connected to solar PV system such as lights, radio, TV, computer, refrigerator, etc.
- Auxiliary energy sources - is diesel generator or other renewable energy sources.

Solar Mechanical Method

In Solar Mechanical Method, the mechanical power required to drive the compressor is generated by solar driven heat power cycle. Rankine cycle is the heat power cycle considered for this process. In Rankine cycle, fluid is vaporized at an elevated pressure by heat exchange with a fluid heated by solar collectors. A storage tank can be included in this process to provide some high temperature thermal storage. The vapor flows through a turbine or piston expander to produce mechanical power. The fluid exiting the expander is condensed and pumped back to the boiler pressure where it is again vaporized. The efficiency of the Rankine cycle increases with increasing temperature of the vaporized fluid entering the expander. Whereas, the efficiency of a solar collector decreases with increasing temperature of the delivered energy. High temperatures can be obtained by employing concentrating solar collectors that track the sun's position in one or two dimensions.

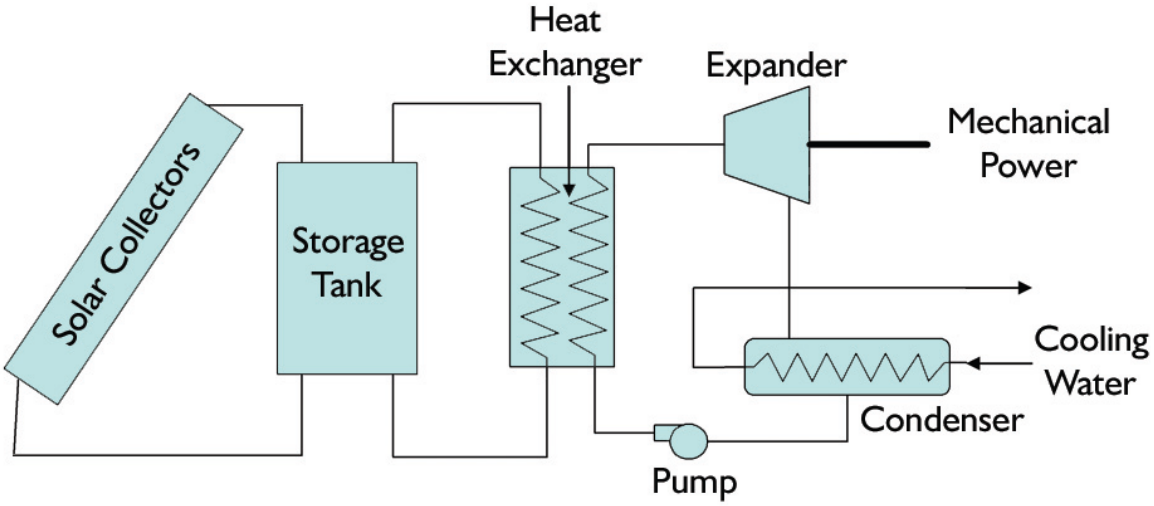

Fig.2- Solar Mechanical Method

The disadvantages of using solar trackers are cost, weight and complexity of the system. If tracking is to be avoided, evacuated tubular, compound parabolic or advanced multi-cover flat plate collectors can be used to produce fluid temperatures ranging between 100°C – 200°C. Both intensity of solar radiation as well as difference of temperature between entering fluid and ambient govern the efficiency of solar collector. The efficiency of such a system is lower than solar electric method using non-concentrating PV modules. Solar Mechanical is advantageous only when solar trackers are used but, the use of such systems is limited to large refrigeration systems only i.e. atleast 1000 tons. **(refer fig. 2)**

Solar Thermal Method

The main advantage of using Solar Thermal Method is that they can utilize more of the incoming sunlight than photovoltaic systems. In a conventional PV collector, 65% of the incident solar radiation is lost as heat whereas in solar collectors over 95% of the incoming solar radiation is absorbed. But all of this is absorbed energy is not converted to useful energy due to inefficiencies and losses. Collection efficiencies for commercial solar thermal collectors are generally more than double that of crystalline photovoltaic solar collectors. A typical solar thermal refrigeration system consists of four basic components - a solar collector array, a thermal storage tank, a thermal refrigeration unit and a heat exchange system to transfer energy between components and the refrigerated space. Selection of the solar array depends upon the temperature needed for refrigeration system. Generally for temperature range 60-100C, flat plate collectors, evacuated tube collectors and concentrating collectors of low concentration can be used. Concentrating collectors are avoided for residential purposes due to high cost of solar trackers. Selection of the thermal storage tank depends upon the type of storage medium and the temperatures desired. Water is mainly selected for its low environmental impact and high specific heat.

Desiccant

A desiccant system is usually an open cycle where two wheels turn in tandem – a desiccant wheel containing a material which can effectively absorb water, and a thermal wheel which heats and cools inward and outward flows. Warm, humid, outside air enters the desiccant wheel where it is dried by the desiccant material. Next, it goes to the thermal wheel which pre-cools this dry, warm air. Next, the air is cooled further by being re-humidified. When leaving, cool, conditioned air is humidified to saturation and is used to cool off the thermal wheel. After the thermal wheel, the now warm humid air is heated further by solar heat in the regenerator. Lastly, this hot air passes through the desiccant wheel so that it can dry the desiccant material on its way out of the cycle. Pre-packaged desiccant is most commonly used to remove excessive humidity that would normally degrade or even destroy products sensitive to moisture. Some commonly used desiccants are silica gel, activated charcoal, calcium sulfate, calcium chloride, montmorillonite clay, and molecular sieves.

Absorption

An absorption refrigerator is a refrigerator that uses a heat source (e.g., solar, kerosene-fueled flame, waste heat from factories or district heating systems) to provide the energy needed to drive the cooling system. Absorption refrigerators are a popular alternative to regular compressor refrigerators where electricity is unreliable, costly, or unavailable, where noise from the compressor is problematic, or where surplus heat is available (e.g., from turbine exhausts or industrial processes, or from solar plants). In absorption, two mainly used cycles are- LiBr (Lithium Bromide) and NH3 (Ammonia Hydrogen). The main difference between them is which substances are used as the refrigerant and absorbent. In a LiBr system, LiBr is the absorbent and water is the refrigerant. In an NH3 absorption system, water is now the absorbent and NH3 is the refrigerant. In both cases, the job of the compressor (in a conventional vapour compression system) is replaced by an absorber and a generator. Concentrated absorbent enters the absorber, which is connected to the evaporator. When refrigerant is boiled off in the evaporator (removing heat from the refrigerated space), vapour (of relatively high pressure) then moves to the LiBr/water absorber where it is absorbed. Next, the mixture moves to the generator where solar heat is supplied to boil off the refrigerant. High-pressure refrigerant vapour then travels to the condenser where heat is rejected to the surroundings to condense the refrigerant back to liquid. Liquid refrigerant goes back into the evaporator, where it can be used again to take in heat from the refrigerated space, which completes the loop. **(refer fig.3)**

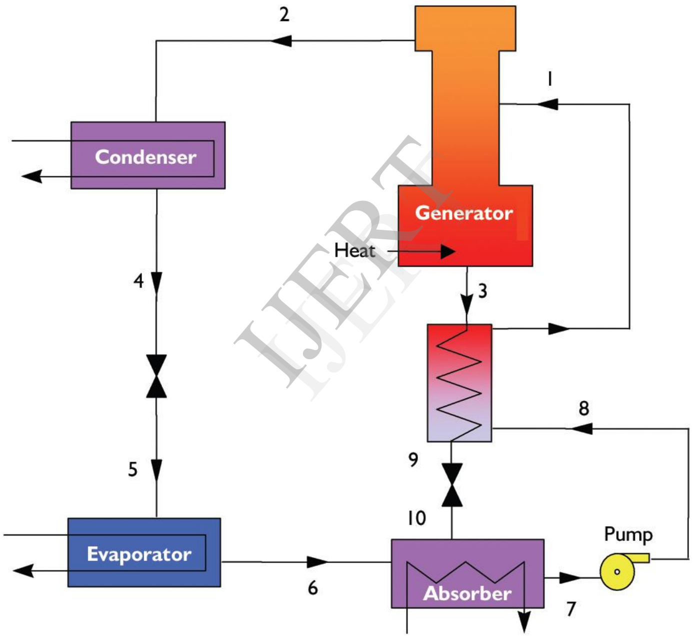

Fig.3- Ammonia-water absorption refrigeration system.

Adsorption

In this cycle, solar heat is directed to a sealed container containing solid adsorbent saturated with refrigerant. Once this reaches the proper temperature/pressure the refrigerant desorbs and leaves this container as pressurized vapour. That is, the vapour has been compressed with thermal energy. This vapour then travels to a condenser where it turns to liquid by rejecting heat to the surroundings. Expanded, low-pressure liquid refrigerant then flows over the evaporator which pulls heat from the conditioned space to boil off the refrigerant. The refrigerant vapour can then be adsorbed again by the cool adsorbent material easily at night. Although there are similarities between absorption and adsorption refrigeration, the latter is based on the interaction between gases and solids. The adsorption chamber of the chiller is filled with a solid material (for example zeolite, silica gel, alumina, active carbon and certain types of metal salts), which in its neutral state has adsorbed the refrigerant.

Cooling Thermal Energy Storage (CTES) System

The most important use of CTES systems is to shift the power consumption from peak to off-peak periods. For this reason these systems are also known as “off-peak cooling” systems. The performance of a TES system is described by its co-efficient of performance (COP). The COP of a system during peak and off-peak hours is defined by the chiller and compressor design. CTES systems are generally classified into three types- chilled water, ice storage and eutectic salt TES systems. Among these techniques, the Chilled Water Storage (CWS) and the Ice Thermal Storage (ITS) systems are the most promising ones in case of the normal applications. The ITS system has the advantages of larger storage volume in comparison with two other systems. However, the COP of the ITS system is much lower than other techniques. In sensible CTES, the storage medium is usually water-based whereas in latent CTES systems, eutectic salts with phase change materials is generally preferred as storage medium. Sensible CTES systems account for most cold TES applications presently. Thermochemical TES may prove useful for cooling TES systems provided ongoing efforts to develop systems are successful. So, in short, the various advantages of using CTES system are:-

- Reduction in electricity bills by shifting the power consumption from peak to off-peak periods.
- Usually the systems with CTES would consume less operating energy than conventional air conditioning (AC) systems due to constant and comparatively lower temperature during the nights.
- Producing off-peak electricity is cheaper as it would consume less fuel.
- Chiller efficiency is improved by shifting the electricity consumption from daytimes to nights when the ambient temperature (Ta) is considerably low.
- The significant air temperature difference across the Air Handling Unit (AHU) reduces the required air volume required for circulation. Hence, smaller AHUs, less duct working and less electrical equipments are required.

Chilled Water Storage (CWS)

It is a famous strategy adopted in many countries to save energy by shifting power consumption from peak hours in the daytime to off-peak hours during the nighttimes by employing chilled water to store cool thermal energy. In the past, prior to the successful evolution of thermally stratified systems, many different types of CWS designs have been developed and employed. Designs of CWS were such in order to primarily avoid temperature mixing of chilled water with return water. However, they often require complex tank configurations or piping systems that are expensive and difficult to operate. The CWS systems currently in use can be classified as (a) labyrinth, (b) baffle, (c) tank series, (d) membrane tank. **(refer fig.4)**

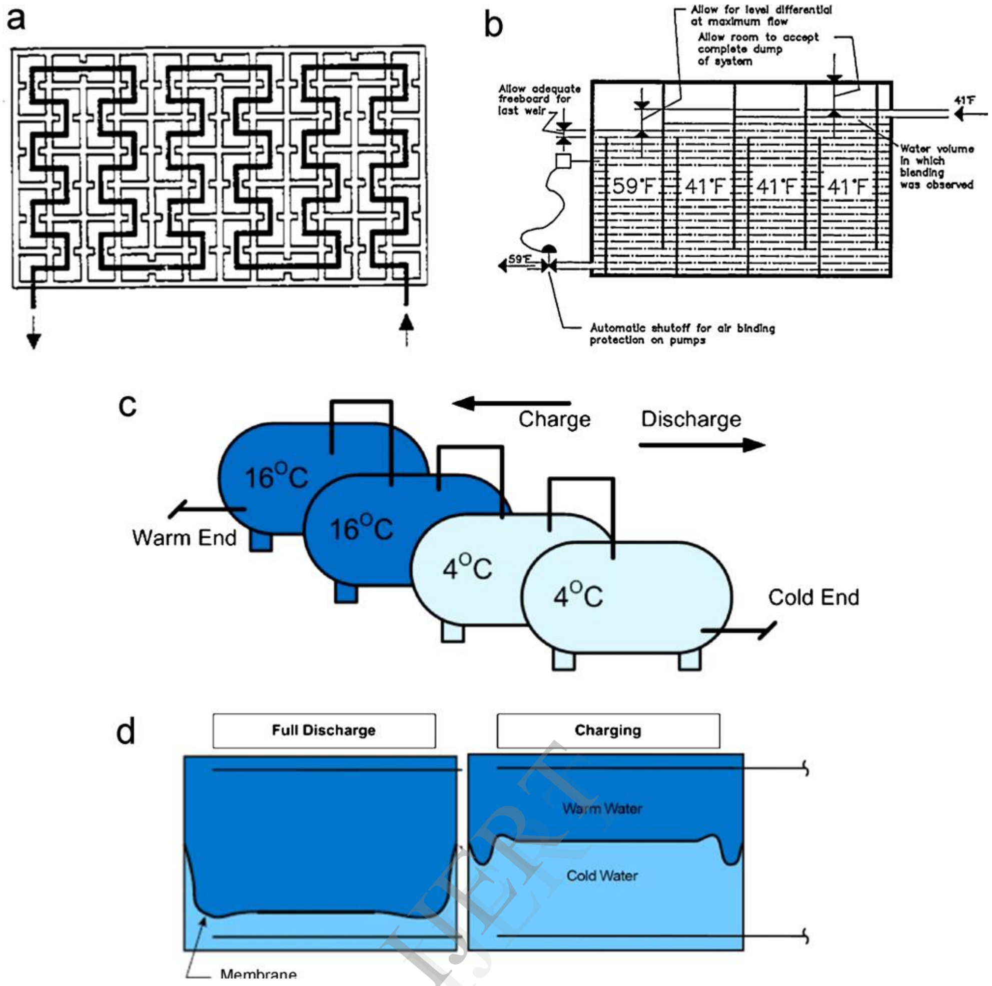

Fig.4- CWS Tanks

Ice Thermal Storage (ITS)

The most popular technique for storing cool thermal energy was the use of ice due to its high latent heat of fusion i.e. h_{sf} = 334 kJ/kg. This method was used especially when the available space was limited. The supplied chiller in this technique must be able to produce charging temperature in the range of -6$_0$C to -3$_0$C in order to produce ice. Investigations revealed that employing the ITS system would downsize the cooling generation devices such as pipes, ducts and AHUs. This downsizing will help in lowering the primary cost of the HVAC system. The ITS storage technologies are generally categorized by their different combinations of storage media, charging or discharging mechanism. ITS systems can be commonly categorized into the following types -

- Ice Harvesters
- Ice slurry
- Encapsulated Ice
- External melt ice-on-coil storage systems
- Internal melt ice-on-coil storage systems

Ice Harvesters

This technique is a dynamic type of ITS system consisting of an open insulated storage tank and vertical plate surface positioned above the tank. A circulating pump brings the water at a temperature of 0_0C on the outer surface of the evaporator, which is fed internally with liquid refrigerant. Normally, thickness of the produced ice varies between 8 mm and 10 mm depending on the length of the freezing cycle. **(refer fig.5)**

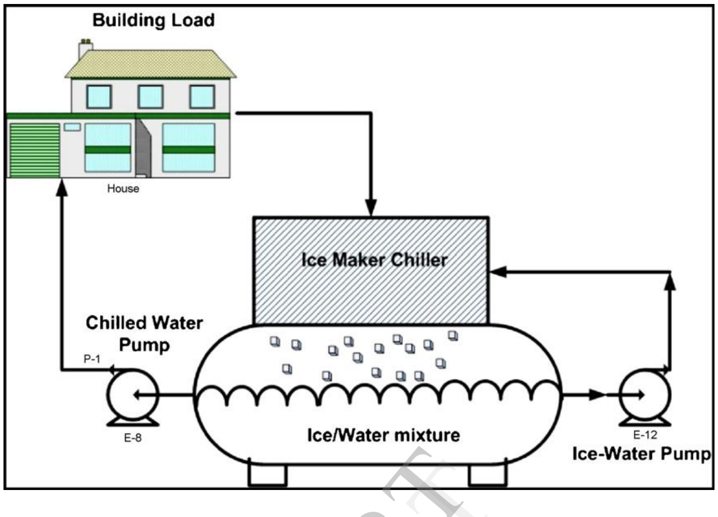

Fig.5- Schematic diagram of a typical ice harvesting ITS system

The ice would then be harvested by feeding a hot gas to the evaporator. The outer surface temperature rises to about 50C causing the ice in contact with the plates to melt and fall into the storage tank. During the discharging period, the chilled water that circulates through the storage tank further reducing the water temperature to cope with the load. Due to the system complexity, only a few manufacturers are involved with these systems, which are normally employed only in special applications.

Ice Slurry

Ice slurry generally refers to a mixture of ice crystals and liquid which is usually an antifreeze solution of water and a freezing point depressant such as ethylene glycol. Ice slurry systems come in a variety of sizes and configurations. But, the most widely applied ice making technology is the scraped surface process. In this process, a typical vapor-compression refrigeration cycle whose evaporator is located on the outside of a tube-in-tube heat exchanger is employed. The inner tube contains the binary antifreeze solution and the water content freezes on contact with the outer cylinder. A rotating scraper lifts off the ice and the ice is then transported through the length of the heat exchanger with the heat transfer fluid thereby increasing the ice content and cooling potential of the heat transfer fluid. Investigations revealed that the heat transfer capacity of the heat exchanger with melting the ice slurry is around 30% more than conventional chilled water flow systems. The advantage of an ice slurry based cool TES system is the fact that the ice storage density can be relatively large when compared to other systems. Also, the ice slurry can be applied directly to any cooling load, since additional heat transfer fluids are not needed as in other ice cooling systems. However, one major drawback of the ice slurry technique is the costly manner in which the ice is produced. A high amount of energy is required to drive the ice scrapers in the scraped ice technique, but new ice making procedures are currently being studied which may hopefully reduce this drawback in future. **(refer fig.6)**

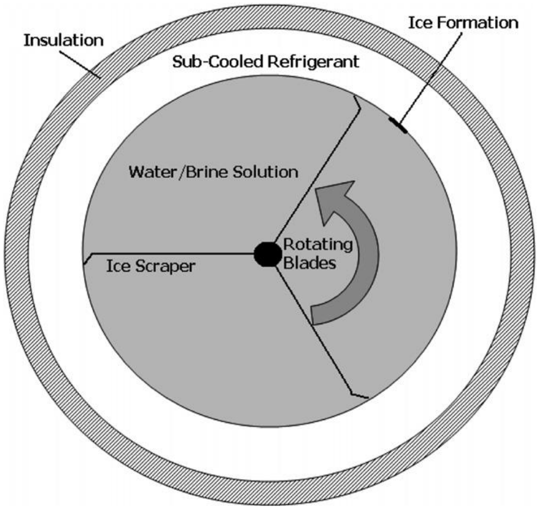

Fig. 6- Cross-sectional schematic of a scraped surface ice slurry generator.

Encapsulated Ice

An encapsulated ice storage system consists of numbers of spheres or rectangular plastic capsules of water immersed in a secondary coolant such as ethylene glycol in a steel or concrete tank. In this method of ice storage, the water is packed into capsules, which in turn are packed into a storage tank. A heat transfer fluid can then be run through the storage tank when heat extraction or input is desired. The simplicity in design in this case occurs where the capsules are mass-produced and used to fill any sized storage tank to meet any cooling load requirements. Typically, the storage tank will be of a cylindrical shape because the cylinder is a relatively low-cost shape to produce which can withstand high pressures and also the surface area-to-volume ratio in cylinders is lower than most other geometries, thereby, allowing for less heat penetration or leakage from the system.

External melt ice-on-coil storage systems

The external melt ice-on-coil TES system is sometimes referred to the ice builder because in this storage system the ice is formed on the outer surface of the heat exchanger coils submerged in an insulated open tank of water. During the charging procedure, a liquid refrigerant or a glycol solution circulates inside the heat exchanger coils and produces ice on the outer surface of the coil. The ice thickness is usually varied between 40 mm and 65 mm depending on the application. During the discharging process, the returned water from the load circulates while passing through the ice tank and cooled down by direct contact with the ice. **(refer fig.7)**

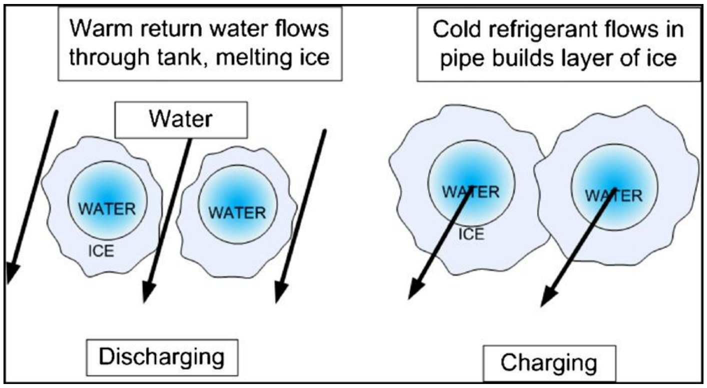

Fig. 7- The charging and discharging procedure of an external melt ice storage system

Internal melt ice-on-coil storage systems

In the internal melt ice-on-coil storage systems the heat transfer fluid such as the glycol solution circulates through winding coils submerged in tanks filled with water. During charging, the low temperature glycol solution flows through the coils inside the tank and produces ice on the coils outside surface. During the discharging process, the warm glycol solution flows through the coils causing ice to melt from the inside out. **(refer fig.8)**

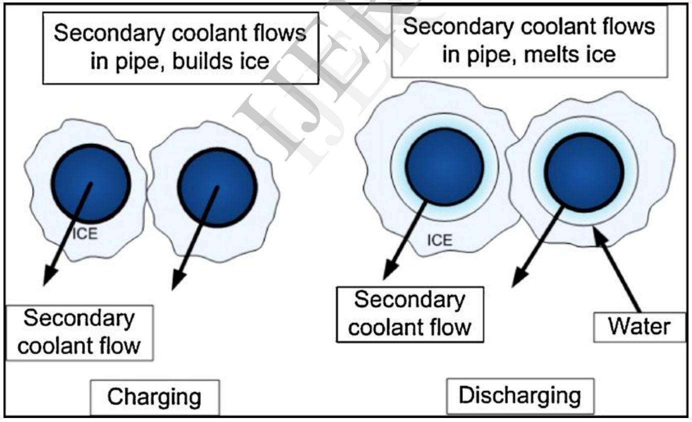

Fig.8- Charging and discharging procedure of an internal ice-on-coil storage system

Literature survey of work carried out by various authors

M. M. Hussain, et al. [1]: The simulation of thermal energy storage (TES) system for HVAC system has been dealt with in this paper. To store cooling capacity, TES system is integrated with conventional HVAC system. Ethylene Glycol is used as a storage medium in this system. Exergy and Energy analyses have been used to determine the thermodynamic performance of the system. Effect of various parameters such as ambient temperature, cooling load and mass of storage on the performance of the TES system has been also studied in this paper. The results of various studies and analyses conducted on TES systems revealed that the storage temperature decreases linearly with time when there is no load and follows the load profile during daytime and decreases linearly with time at the end. Also, it was found out that the storage temperature decreases slightly with increase in ambient temperature when there is no load. COP of the system was found out to decrease sharply with small increase in storage temperature. It was also discovered that for all mass flow rates of discharging fluid, the energy efficiency of the system was found out to be nearly 80%. But, the exergy efficiency of the system decreased with increase in mass flow rate of the discharging fluid and increased with increase in reference temperature.

Fakeha Sehar, et al. [2]: In this paper, the impact of ice storage systems on the chiller energy consumption for large and medium-sized office buildings in diverse climate zones has been investigated. The various studies indicated that the systems with ice thermal storage (ITS) have higher chiller energy consumptions than the conventional non-storage systems because of the day and night operation of the chiller. By discharging ice storage during the peak hours, the ITS were able to achieve peak energy savings by reducing or even by completely eliminating the chiller operation during the daytime. It was also noticed that climatic zones with summers having high temperatures and relative humidity (RH) increase not only the building cooling load but also the chiller energy consumption by decreasing the cooling intensity of the condenser water, for example- Miami and Las Vegas. But, climate zones with less extreme summers have lower chiller energy consumption due to lower building cooling loads and more cooling of condenser water, for example- Seattle.

Mehmet Azmi Aktacir, [3]: In this study, a PV-powered multi-purpose refrigerator system has been erected to investigate experimentally its daily and seasonal operating performances based on semi-arid climatic conditions of Sanliurfa province in Turkey. It is one of the sunniest rural regions in the world and hence the need for refrigeration is critical. The overall results revealed that PV-refrigerator system can be reliably used in places where the local grid was unreliable and the refrigeration need is critical. On observation, the following results were observed- Low temperature of 10.6°C was reached in the refrigerator, the highest energy amount produced by PV panels was recorded between 11:00 am and 14:00 pm, amount energy consumed by the refrigerator was determined to be 347.7 Wh/day, the amount of energy stored in the battery bank was 78.2 Wh/day while the amount of electric energy produced by photovoltaic panel was 425.9 Wh/day.

Sanford A. Klein and Douglas T. Reindl, [4]: In this paper, it was stated that the energy use associated with refrigeration system operation and the environmental impacts associated with its generation and distribution often outweigh the choice of environmental friendly refrigerants. In this article, three approaches to use solar energy for refrigeration at temperatures below 0C were reviewed and their operating characteristics were compared. The COP of all the three refrigeration cycles- Solar Electric, Solar Mechanical and Absorption cycles were compared and found to be low due to various barriers like firstly, the solar refrigeration systems are complicated, costly and bulky because of the necessity to locally produce the power required for operation and secondly, the energy source for these systems i.e. solar energy is variable which requires energy storage system that further adds to the system size and cost. The PV system was most viable of all other systems especially for small capacity portable systems whereas the absorption systems were more feasible for large stationary refrigeration systems.

S.M. Hasnain, et al. [5]: In this paper, the incorporation of ice thermal storage with conventional air conditioning systems in Saudi office was studied. This incorporation reduced the peak electric demand, cooling plant capacity and new electric connection charges of an office building. For this study, two different scenarios were studied. The partial ice storage technique adopted for this study reduced the peak electrical load for Scenario-I and Scenario-II, by 15 and 23%, respectively. It was estimated that an ice storage system would reduce the peak cooling load between 35 and 40% in this type of Saudi buildings. The savings that resulted by downsizing the cooling plant overcame the cost of storage and the additional interface equipment. Similarly, it wass also estimated that in Saudi Arabia, the use of ice storage systems with gas turbines for inlet air cooling will increase the turbine's output by 30% and reduce its heat rate by 10% at a mere fraction of the cost of installing the additional capacity for power generation in order to meet the summer peak demand.

Todd Otanicar, et al. [6]: In this paper, a variety of solar cooling schemes have been economically and environmentally analyzed to reveal some key details regarding system choice. For solar electric cooling the system, the cost is highly dependent on the system COP when PV prices remain at the current levels but when prices are lowered the impact of COP on cost diminishes. For solar thermal cooling, the cost of solar collection is much lower as a percentage of the overall cost, but the cost of the refrigeration system represents a larger percentage of the total cost. Additionally, the paper reveals that the costs for solar thermal cooling are not projected to decrease as much as PV cooling over the next 20 years due to the relatively stable cost of collection and storage. Solar electric cooling, even with the associated impact of refrigerants with global warming impact, have a lower projected emission value of carbon dioxide per kWhr of cooling than any of the thermal technologies due to the much larger COP values associated with solar electric cooling. One additional favorable aspect to solar electric cooling systems is the collector area foot print i.e. for solar PV systems, expected sizes in 2010 were between 24 and 48 m2 as compared to 78 and 106 m2 for solar thermal systems depending on system COP.

David MacPhee, et al. [7]: In this paper, the solidification process for an encapsulated ice TES is investigated. Using Fluent 6.3 software, a domain consisting of one capsule containing water as the PCM and with an outer shell made of PVC is simulated from an initial temperature of 275 K until completely frozen, using ethylene glycol as the heat transfer fluid (HTF). The purpose of this study is to assess how changing capsule geometry, inlet HTF temperature and flow rate affect the performance of the charging process. Using both energy and exergy analyses, efficiencies were calculated for each simulation, while varying the inlet temperature from 267 to 271 K, and choosing three flow rates, Q = 0.87 l/s, 1.74 l/s and 2.61 l/s. The results indicate that considerable cost and energy savings could be realized by utilizing a higher HTF temperature, perhaps a few degrees below the solidification temperature of the PCM. It is possible for the designers to increase flow rate to make up for the increase in charging time associated with this increase in HTF inlet temperature since, the losses associated with viscous dissipation and hence, pressure drop have been shown to be inconsequential compared to other modes of losses. Doing so should allow for an increase in efficiency while still maintaining a working and effective encapsulated ice TES system.

B. Rismanchia, et al. [8]: The work in this paper investigated the feasibility and potential of employing ITS systems for the cooling application of office buildings in Malaysia along with the economical and environmental benefits of utilizing these systems. This study is mainly conducted due to the vast potential that the country has, the statistical data shows that in Malaysia, AC systems are the major energy consumers in office buildings with around 57% share. However, they are not well promoted in Malaysia and their potentials are not yet well investigated. The overall results show that the full storage strategy can reduce the annual costs of the air conditioning system by up to 35% while this reduction is limited to around 8% for a load levelling strategy. By comparing the installation, maintenance and electricity costs of the conventional system with the ITS system, it was found that for the full storage strategy it will take between 3 and 6 years for the benefits of the investment to be equal with the investment. For the load levelling strategy this period varies between 1 and 3 years. The comparison results between the conventional AC system and the ITS system indicate that a proper design could lead to lower energy consumption due to better utilization of the equipment. It shows that the load levelling strategy consumes around 4% less energy than the conventional AC systems. The annual energy saving stated that the annual CO2 emission reduction for load levelling strategy varies from 3000 to 60,000 ton for the total system capacities of 352 and 7034 kW.

David MacPhee, Ibrahim Dincer, [9]: In this paper, a performance assessment of four main types of ice storage techniques for space cooling purposes, namely ice slurry systems, ice-on-coil systems (both internal and external melt), and encapsulated ice systems is conducted. The ice making techniques are compared on the basis of energy and exergy performance criteria including charging, discharging and storage efficiencies, which make up the ice storage and retrieval process. Losses due to heat leakage and irreversibilities from entropy generation are included. A vapor-compression refrigeration cycle with R134a as the working fluid provides the cooling load, while the analysis is performed in both a full storage and partial storage process, with comparisons between these two. In the case of full storage, the energy efficiencies associated with the charging and discharging processes are well over 98% in all cases, while the exergy efficiencies ranged from 46% to 76% for the charging cycle and 18% to 24% for the discharging cycle. For the partial storage systems, all energy and exergy efficiencies were slightly less than that for full storage, due to the increasing effect wall heat leakage has on the decreased storage volume and load. The results show that energy analyses alone do not provide much useful insight into system behavior, since the vast majority of losses in all processes area result of entropy generation which results from system irreversibilities.

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