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Liquid paraffin wax solar absorption refrigerator system

Farhan Lafta Rashid, Ibrahim Kaittan Fayyadh, Ahmed Hashim, Zainab Omran Muse and Zainab Zouher Knesh

Ministry of Science and Technology, Baghdad-Iraq.

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ABSTRACT

An available gas fired diffusion-absorption heat pump 150 liter (5ft) refrigerator has been modified by substituting the original heat input by transferring solar thermal energy from solar collector to the generator. At the beginning, a pipe with 90cm height, filled with hot water (97^{o}C) is used as a generator heat input but the Ammonia vapor does not generate because the temperature is low to allow Ammonia-Water mixture to boil. Therefore the Water is replaced by high boiling point fluid (liquid paraffin wax), boiling point 310°C), and the generator with pipe with 30cm height and 5cm in diameter. Then Ammonia vapor generates at fluid temperature of 140^{o}C up to 190^{o}C where the pipe near the condenser becomes hot. This mean that the Ammonia vapor generate up to the condenser. The flow rate required to supply heat input to generator, the solar collector receiver area and the volume of hot fluid storage required to operate the refrigerator for 24 hours has been calculated.

Introduction

Energy supply to refrigeration and air-conditioning systems constitutes a significant role in the world. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds . According to the statistics survey by JARN1 and JRAIA2, the demand for air conditioners worldwide has the fundamental tendency of steady increase. The global growth rate is about 17%.

The cooling load is generally high when solar radiation is high. Together with existing technologies, solar energy can be converted to both electricity and heat; either of which can be used to power refrigeration systems. The idea is not new, a solar-driven refrigerator was first recorded in Paris in 1872 by Albel Pifre. A solar boiler was used to supply heat to a crude absorption machine, producing a small amount of ice. Later, solar powered refrigeration systems have been installed worldwide in many countries e.g. Australia, Spain, and the USA. Most are thermally driven absorption systems, designed for air-conditioning purposes. Being provided with a good electricity grid worldwide, people are, however, more likely to choose a vapour compression air-conditioning system.

Due to energy shortage in some regions, especially after the energy crisis of the 1970's, solar energy as a renewable energy source has once again become a popular energy source. Research and development in the solar energy field has grown rapidly, along with research in solar cooling. With the invention of the DC-motor, photovoltaic (pv) technology was first used for pumping water. Later the pump motor was modified to drive the vapour compression system. PV-driven water pumps and refrigerators have since become a relatively large business. Subsequently, researchers have integrated so-called Peltier coolers with PV-panels to simple, yet inefficient solar coolers. These systems are used in the cold chain projects of the World Health Organization [8].

There are a few commercial systems currently available, e.g. a vapor-compression/PV and an absorption/thermal collector. Solar air-conditioning systems have also been regularly in operation. Commercial absorption cooling machines e.g. Yazaki (Japanese) are available. According to Hans-Martin Henning (Fraunhofer Institute Ise, Germany), about 70 solar air-conditioning systems driven by the solar energy are in operation in Europe, with a total cooling capacity of 6.3 MW, corresponding to 17 500 m^2 of installed solar thermal collector area [7].

Design of solar driven cooling system

Any solar cooling system design essentially consists of two parts: the cooling unit that uses thermal cycle is not different from those used in conventional refrigerators, and heat source with the solar flat plat collector or focus operation.

The cooling unit

The absorption diffusion refrigerator machine is designed according to the operating principles of the refrigeration machine mono pressure invented by Platen and Munter (Unique Gas Products Ltd). This machine used three operating fluids, water as the absorbent, the ammonia as refrigerant, and hydrogen as inert gas used in order to maintain the total pressure constant, figure (1) shows this system which is composed of the principal following elements:

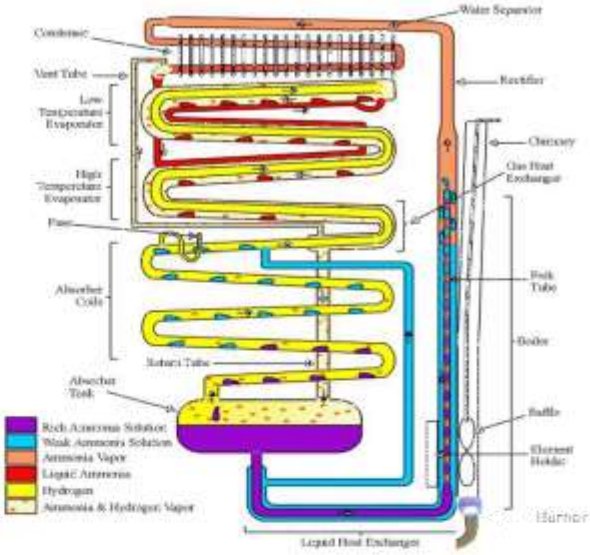
The boiler

A precise heat (electric heater element or gas flame) is applied to the boiler to begin operation. Heat is transferred from the outer shell of the boiler through the weak ammonia solution to the perk tube.

The perk tube is provided with a rich ammonia solution (a high percentage of ammonia to water) from the absorber tank. When heated, the ammonia in the rich ammonia solution begins to vaporize (sooner than the water would) creating bubbles and a percolating effect. The ammonia vapor pushes the now weakening solution up and out of the perk tube. The ammonia vapor (gas) leaving the perk tube goes upward towards the top of the cooling unit, passing through the rectifier. The rectifier is

Tele:
E-mail addresses: engfarhan71@gmail.com

just a slightly cooler section of pipe that causes water that might have vaporized to condense and drop back down. The water separator at the top of the cooling unit (only on some models) prevents any water that might have escaped the rectifier to condense and fall back. After this point, pure ammonia vapor is delivered to the condenser. Meanwhile, back at the perk tube, the weaker solution expelled from the perk tube by the ammonia vapor drops into the weak ammonia solution surrounding the perk tube. Here, a little more ammonia vapor is generated and rises. The weak ammonia solution flows down ward and through the outer shell of the liquid heat exchanger, where heat is transferred to the rich ammonia solution on its way to the perk tube. The weak ammonia solution then flows to the top of the absorber coils and enters at a cooler temperature.



Fig(1). Platen- Munter Diffusion Absorption Refrigerator [12]

The condenser

Ammonia vapor enters the condenser where it is cooled by air passing through the metal fins of the condenser. The cooling effect of the condenser coupled with a series of step-downs in pipe size forces the ammonia vapor into a liquid state, where it enters the evaporator section.

The evaporator

Liquid ammonia enters the low temperature evaporator (refrigerator/freezer) and trickles down the pipe, wetting the walls. Hydrogen, supplied through the inner pipe of the evaporator, passes over the wet walls, causing the liquid ammonia to evaporate into the hydrogen atmosphere at an initial temperature of around -20º F. The evaporation of the ammonia extracts heat from the refrigerator/freezer. At the beginning stages, the pressure of the hydrogen is around 350 psi (pounds per square inch), while the pressure of the liquid ammonia is near 14 psi. As the ammonia evaporates and excess liquids continues to trickle down the tube, its pressure and evaporation temperature rise. (Based on Frostek 240 Freezer) The liquid ammonia entering the high temperature evaporator (refrigerator portion) is around 44 psi, while the pressure of the hydrogen has dropped to 325. Under these conditions, the evaporation temperature of the liquid ammonia is +15º F. Heat is removed from the refrigerator box through the fins attached to the high temperature evaporator. The ammonia vapor created by the evaporation of the liquid ammonia mixes with the already present hydrogen vapor, making it heavier. Since the ammonia and hydrogen vapor mixture is heavier than the purer hydrogen, it drops down through the evaporators, through the return tube to the absorber tank. (Based on Frostek 240 Freezer).

The absorber

When the ammonia and hydrogen vapor mixture enters the absorber tank through the return tube, much of the ammonia vapor is absorbed into the surface of the rich ammonia solution, which occupies the lower half of the tank. Now lighter, the ammonia and hydrogen mixture (now with less ammonia) begins to raise up the absorber coils.

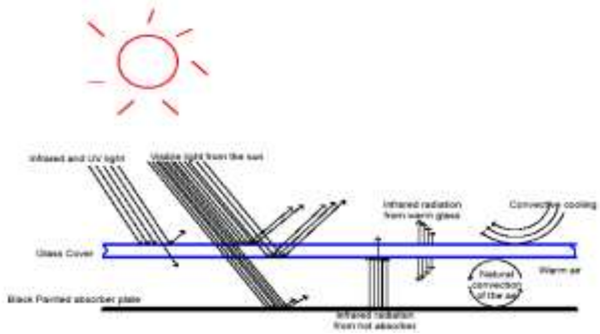
The weak ammonia solution trickling down the absorber coils from the top (generated by the boiler) is "hungry" for the ammonia vapor rising up the absorber coils with the hydrogen. This weak ammonia solution eventually absorbs all the ammonia from the ammonia and hydrogen mixture as it rises, allowing pure hydrogen to rise up the inner pipe of the evaporator section and once again do its job of passing over the wetted walls of the evaporator. The absorption process in the absorber section generates heat, which is dissipated.

The Fuse

The fuse on many cooling units and in this graphic is a steel tube, the end of which is filled with solder. The plug is hollow and filled with solder. In either case, the fuse is the weak link of the system. If pressure inside the cooling unit were to rise beyond a reasonable level for some reason, the fuse is designed to blow and release the pressure. This would make the cooling unit inoperable, but is necessary for safety.

The solar Collectors

The major energy gains in the receiver in a solar collector are from the direct absorption of visible light from the sun and, additionally, the absorption of infrared radiation from the warm glass as show in figure (2). Important energy losses are infrared radiation emission, convective heat due to natural convection between the receiver and glass, as well as conduction of heat through the rear and sides of the collector. Therefore, the efficiency of the solar collector depends on all of these factors. The efficiency of the solar collector sub-system can be defined as the ratio of useful heat output to the total incident solar radiation (insulation) [8].



Figure(2) Energy Flows in a Single-Glazed Collector

In the following efficiency definition, it is assumed that radiation is in the hemispherical region, all rays reach the receiver, and the multiple reflections between the cover and receiver are neglected (rays reflected back from the receiver to the glass are not accounted for). The solar collector efficiency can be written as [8, 4]:

$$\eta = F_m\left(\eta_{opt} - \frac{U_L\left(T_{r,avg} - T_a\right)}{I}\right) \qquad (1)$$

F_m is called the collector efficiency factor or a heat transfer factor. The value of F_m depends on the type of the collector and operating conditions. Typical values of F_m is in the range of 0.8-

0.9 for non-evacuated air collectors, 0.9-0.95 for non-evacuated liquid collectors, and 0.95-1 for evacuated collectors .

In essence, it is easier to measure the temperature of the heat transfer fluid than to measure the temperature of the receiver surface temperature. Therefore, the solar collector efficiency is often written in terms of the temperature of the inlet (Ti) and outlet (To) temperature of the heat transfer fluid. The average temperature of the receiver can be assumed to be [10, 8, 9 & 11]:

$$T_{r,avg} = \frac{T_{ri} + T_{ro}}{2}$$

The average temperature of the receiver, $T_{r,avg}$ can be replaced by the temperature of the fluid entering the collector, T_{in} , if the useful energy is divided by a 'heat removal factor', F_R, defined as the ratio of useful energy if $(T_i - T_a)$ is used rather than $(T_{r,avg} - T_a)$. Note that the heat removal factor (F_R) is a function of the rate of flow of heat transfer fluid. The efficiency of the solar collector can be defined as [10, 8, 11, and 4]:

$$\eta = F_R\left(\eta_{opt} - \frac{U_L(T_{ri} - T_a)}{I}\right) \quad \text{.....................................(2)}$$

Or

$$\eta = F_R(\tau\alpha)_e - F_R U_L \frac{(T_{ri} - T_a)}{I} \quad \text{............................. (3)}$$

F_R is the collector heat removal factor. The later equation is based on the 'Hottel-Whillier-Bliss' Equation. The value of factors $F_R(\tau\alpha)e$ and F_RU_L depend on the type of the collectors, layer of the cover glass and selective material. Typical values of these factors are shown in Table (1) [9] :

Concentrating Solar Collectors

Two types of line-axis concentrating solar thermal collectors are commonly used today: a Compound Parabolic Concentrating (CPC) and Parabolic-trough Concentrating (PTC). The simple structures of these types are shown in Figure (3).

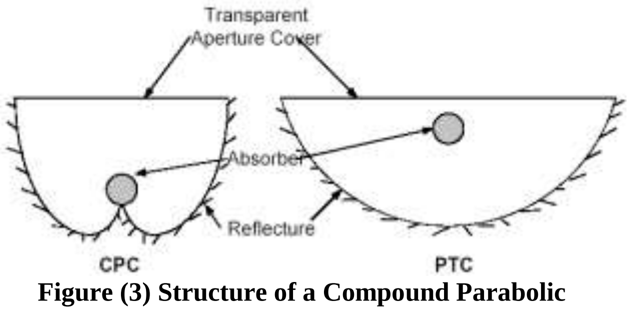


Figure (3) Structure of a Compound Parabolic Concentrating Solar Collector (CPC) and a Parabolic-Through Concentrating Solar Collector (PTC)

The concentration ratio (C) describes the characteristics of the concentrating solar collector. It is the ratio of the incident solar radiation area (A_{in}) to the receiver area (Ar).

$$C = \frac{A_{in}}{Ar} \quad \text{...(5)}$$

The concentrating optical solar collector is suitable for high temperature applications (e.g. temperatures >150°C). The large er area induces high heat losses. By concentrating the radiation incident of the aperture onto a smaller receiver, the heat losses per receiver area can be reduced. Tracking system is necessary to follow the movement of the sun in order to maintain concentration. The compound parabolic concentrator (CPC) is however not necessary for tracking since the concentration ratio is quite low. The CPC can, therefore, play an important role in solar cooling in the future. The main contribution is the direct (not the diffuse) solar radiation which differs somewhat from the flat-plate solar collector.

Concentrators can be divided into two categories: non-imaging and imaging concentrators. The non-imaging concentrator does not produce a clearly defined image of the sun on the receiver; but distributes radiation from all parts of the solar disc onto all parts of the receiver. The values of the concentration ratio of linear non-imaging collectors are quite low, generally below ten. The imaging concentrator is similar to a simple camera lens, which can form images on the receiver.

The modified Solar Driven Absorption System

The present design study is adapted as gas fired diffusion-absorption heat pump 150 liter (5ft) refrigerator which is available in the market and modify it by removing the original heat input source (kerosene flam, chimney and the jacket of electrical heater) and substitute it with solar heat input source.

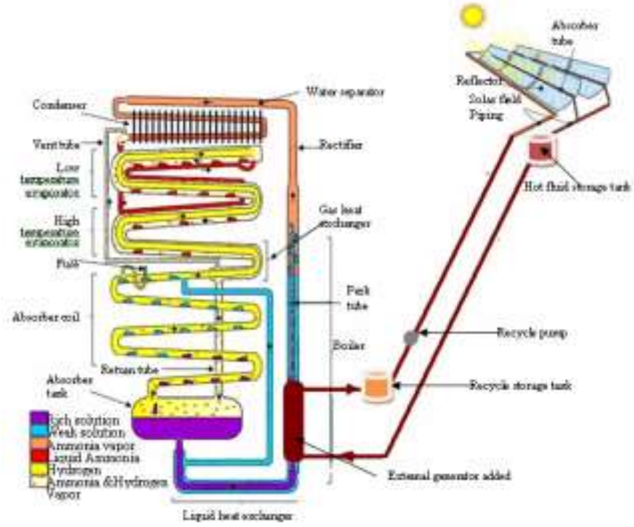


Figure (4) The Modified Solar Driven Platen-Munter Diffusion Absorption Refrigerator

Two attempt were done, first with pipe of height 90 cm, the bottom section, 40 cm height with diameter of 5cm, and upper section, 50cm height with diameter of 4 cm, around the original generator pipe of refrigerator, using as heat Input generator, fill with hot water maintaining at temperature of 97^{o}C ,but the refrigerator is not operate because the temperature of water is not enough to allow the ammonia–water mixture to boil and no temperature gradient along the pipe height where the heat pump occurs, and second attempt with a pipe 30 cm height and diameter of 5 cm around the bottom section of original generator pipe of refrigerator, using a fluid with high boiling point to reach the temperature at which ammonia vapor generation, this was observed when working fluid temperature inlet the external generator(pipe added) reach 140^{o}C where the rectifier pipe becomes hot . In this work liquid paraffin wax was used as a working fluid (boiling point 310 C^o).Figure (4) shows the pipe added and all the parts of the cooling system.

The operating pressure of the cooling unit (Platen-Munter Refrigerator, 150 liter (5ft)) is 23bar, concentration of rich solution is 33%, concentration of weak solution is 12%, and 1kg of ammonia vapor leave the generator toward the condenser need 649kcal.The complete details of Platen-Munter refrigerator(thermodynamic cycle, mass, and heat transfer) on web site[3].

From the T\Log diagram (Carl) the boiling point of rich ammonia-water mixture (33%) is 130^{o}C and the weak mixture(12%) temperature at 23bar is about 190^{o}C .To operate the cooling unit with above condition, inlet generator temperature about 200^{o}C, and outlet temperature about 140^{o}C must be supplied from solar concentrator, then the flow rate of the working fluid required to achieve this operation is calculate as follow:

In this study 2.52hr was measured to generate 1kg of ammonia with 649kcal ,then the energy demand of the generator is :

$$Q_g = \frac{649}{2.52} = 257.5\,\text{kcal}/\text{hr}$$
$$= 257.5 \times 1.166667 = 300\,\text{W}$$

$$Q_g = m\,cp\,\Delta T \quad \text{.......(6)}$$

$$\Delta T = (T_{go} - T_{gi})$$

The specific heat (cp) of liquid paraffin wax is 2.9J/g ^{o}C, then the mass flow rate of heat exchange fluid required (liquid paraffin wax) can be calculated based on the proposed entrance and exit temperatures of the oil in the generator (Arias-Varela and et. all):

$$m = \frac{300}{2.9 \times (200 - 140)} = 1.724\,g/s$$

=6.206 kg/hr

The density of liquid paraffin wax is 0.93 g/cm^3 then:

The volumetric flow rate is :

6.206/0.93= 6.673 liter/hr

The required hot fluid volume for 24hr is:

6.673x24=160.15 liter per day

The area of the solar collector (Parabolic-trough Concentrating (PTC) collector, shown in figure(4) required by the system was determined based on the quantity of energy demanded and the mass flow of required heat exchange fluid. The energy demand of the generator is 300W (considering a safety factor of 15%,i.e Q_g=345W).

To determine the efficiency of the solar collector it is necessary to know the temperature difference and the solar radiation. The receiver inlet and outlet temperatures were obtained to be 130^{o}C and 200^{o}C, respectively, and the ambient temperature is 30^{o}C. For an average of six hours of effective solar radiation, the value of 1000W/m^2, then from Equation(3),and table(1) the efficiency of the solar collector is:

$$\eta = 0.7 - 2.5\frac{130 - 30}{1000} = 0.45$$

Then the output useful energy per unit area of receiver is :

$$\frac{Q_{out}}{A_r} = 0.45 \times 1000 = 450\ \text{W/m}^2$$

This result in a total absorption (receiver) area of:

$$A_r = \frac{345}{450} = 0.77\ \text{m}^2$$

The required outside wall temperature of the receiver is calculated from the following equation:

$$\frac{Q_{out}}{A_r} = h(T - T_{r,ave}) \quad \text{.......(7)}$$

$$T_{r,ave} = \frac{T_{ri} + T_{ro}}{2} = \frac{130 + 200}{2} = 165^o C$$

Where T_i and T_o are inlet and outlet temperatures of receiver, respectively, and h is the convection heat transfer coefficient =8W/m^{2o}C.Then:

$$T = \frac{450}{8} + 165 = 221.25^o C$$

The thermal output Q_{out} of concentrating collector operating at temperature T is given by:

$$Q_{out} = Q_g = F_m(\tau\alpha)_e A_{in} I - F_m U_L A_r (T - T_a) \quad \text{.......(8)}$$

Dividing equation (8) by A_r yield:

$$\frac{Q_{out}}{A_r} = F_m(\tau\alpha)_e \frac{A_{in}}{A_r} I - F_m U_L (T - T_a)$$

F_m=0.9, $(\tau\alpha)_e = 0.8$, U_L=8W/m^2.^{o}C and I=1000W/m^2 then:

$$\frac{A_{in}}{A_r} = \frac{0.9 \times 8(221.25 - 30)}{720} + 450 = 2.54$$

Then:

A_{in}=0.77×2.54=2 m^2

Heat storage

Heat storage tank is shown in figure (4), allows a solar thermal plant to produce power at night and on overcast days. This allows the use of solar power for base load generation as well as peak power generation, with the potential of displacing both coal and natural gas fired power plants. Additionally, the utilization of the generator is higher which reduces cost.

Heat is transferred to a thermal storage medium in an insulated reservoir during the day, and withdrawn for power generation at night. Thermal storage media include pressurized steam, concrete, a variety of phase change materials, and molten salts such as sodium and potassium nitrate.

Heat transport refers to the activity in which heat from a solar collector is transported to the heat storage unit. Heat insulation is vital in both heat transport tubing as well as the storage vault. It prevents heat loss, which in turn relates to energy loss, or decrease in the efficiency of the system.

Conclusions

Solar cooling systems strongly depend on local conditions e.g. solar radiation, ambient temperature, or cooling load. Systems should therefore be specifically designed for each location, thereby obtaining the best performance. For thermally-driven systems, a solar cooling system requires less solar collector area per cooling demand (kWh). One severe restriction for solar cooling in general is the heat rejection temperature. Heat sink temperatures must be kept as low as possible in order to maintain a stable operation and high performance.

A good local heat sink such as a lake, a river or the sea or even a cooling tower can be used with additional parasitic energy consumption for the latter. The best solar cooling locations are therefore located near sufficient solar radiation and a good heat sink.

Solar driven absorption refrigerator need less initial operating time than gas fired refrigerator, when increase the working fluid flow rate at initial time. This refrigerator is expensive compare with gas fired and electrical refrigerators but it is active when the house is complete work with solar energy (heating, washing, cooking, …etc) and in the remote areas (out of electrical grid).The refrigerator is not operate when the working fluid from collector pass along the whole boiler tube because no temperature gradient occurs.

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Table(1) The Value of $F_R(\tau\alpha)_e$ and F_RU_L for Some Type of Solar Collector[8]

Solar Collector Type	$F_R(\tau\alpha)_e$	F_RU_L (W m^{-2} K^{-1})
Flat-Plate, Selective-Surface, Single-Glass Cover	0.80	5.00
Flat-Plate, Selective-Surface, Double-Glass Cover	0.80	3.50
Evacuated Tubular Collectors	0.80	Range 1-2
Parabolic-Trough Concentrating solar collector (PTC)	0.70	2.5