Development of a simple intermittent absorption solar refrigeration system

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Abstract  A simple solar energy powered intermittent absorption refrigeration system was designed, fabricated and tested. The system uses a generator charged with ammonia and water. The heat source is a solar radiation collector that collects and radiates solar thermal energy onto a black body generator. The generator drives the refrigerant around the system through a condenser and an evaporator. The system was evaluated by leaving it outside under solar radiation and monitoring temperatures at various points inside the collector, the generator, and the evaporator through the use of thermocouple sensors. The average highest and lowest temperatures inside the solar collector were 100°C and 40°C respectively. The average lowest refrigeration temperature was 4°C. The coefficient of performance (COP) of the system was estimated at 0.487.

Keywords  solar refrigeration; heat powered cycles; solar thermal applications

Nomenclature

A  cross sectional area of the outside wall of the refrigeration unit m²
C₃  specific heat capacity of the tomato J kg⁻¹°C⁻¹
E  air change factor per 24 hours
Eₜ  energy absorbed by 1 m² of surface in Dschang per day, kJ m⁻²
fᵢ  inside film or surface conductance W m⁻² °C⁻¹
fₒ  outside film or surface conductance W m⁻² °C⁻¹
h₃₉ (−33.4°C)  specific enthalpy of the saturated ammonia vapour at −33.4°C
h₉₃ (26°C)  specific enthalpy of the saturated ammonia liquid at 26°C
k  thermal conductivity of the insulation material W m⁻² °K⁻¹
M  mass of the tomato in kg
Ma  mass of ammonia liquid kg
Q  amount of energy to be removed from the infiltration air kJ m⁻³
Qₐ  heat from in coming air or infiltration load kJ
Qₑ  quantity of energy necessary to vaporise ammonia in the system (1099.3 kJ)
Qₙ  heat gain to the refrigerator from its environment kJ
Qᵢ  internal heat kJ
Qₚ  heat generated by the refrigerated product kJ
Qₚᵣ  heat produced by the respiration of the product kJ
Qₚₛ  Product cooling load kJ
Qᵣ  rate of heat gain to the refrigerator W
Q₉  Refrigeration load kJ
Introduction

The continuous increase in world population has given rise to a gradual increase in world energy demands. The gradual rise in the cost of electricity due to energy crises is a serious handicap for the socio-economic development of the rural and urban population. At the moment about one in four people in the world has no access to enough energy sources sufficient for their needs [1]. About two billion inhabitants of the developing countries have no access to electricity and about one billion depend only on biomass as a source of energy [1]. Industrialized countries utilise fossil fuels such as carbon, petrol and natural gas for various domestic and industrial applications. The consumption of these fuels contributes immensely to the destruction of the environment. It has been estimated that by the year 2100 the temperature of the world may be increased by up to $3.5^\circ$C causing irreversible changes in the world climate [2].

The difficulties involved in the acquisition and distribution of conventional energy sources in developing countries due mainly to the poor road infrastructure, and the high cost of installation of hydroelectric dams and nuclear power stations have given rise to much interest in renewable energies in general and solar energy in particular. In some developing countries, despite the efforts by most governments to meet the energy needs of the growing population, only a very little percentage of the population has access to conventional forms of energy.

Because of these problems it is necessary to look for other sources of energy that are easy to harness and that do not require long distances for transportation; energy sources that are gentle to the environment, renewable and cheaper to exploit. The availability of these sources would create a lot of small-scale economic activities and generally improve the quality of life of the rural population. Harnessing solar energy and other forms of renewable energies seem to be the most economically viable for enclave rural areas [2].
Good health and energy are interdependent factors, which determine to a great extent the progress of development of the rural sector. Thirty-eight countries in the world that have the highest infant mortality rate are those in which over 73 percent of the population live in the rural areas [3]. Renewable energy sources that could power some of the primary health equipment can considerably help in reducing infant mortality in rural areas, improve their health status, and improve on their intelligence. This in turn will have a major impact on the agricultural productivity of the rural population.

A solar refrigeration system would help in the storage of essential drugs, vaccines and foods that cannot be kept in the rural areas due to lack of energy for refrigeration. In urban areas the refrigeration system could also help in reducing the energy load demanded from the national grid line thereby easing out supply. This is a very important factor in ‘demand side’ energy management. During periods of power failure, much refrigerated food meant for domestic and commercial consumption goes bad bringing about a lot of losses. A solar refrigeration system would use clean energy that does not pollute the environment with refrigeration gasses. The aim of this research was to develop an appropriate technology refrigeration system for the rural masses taking into consideration their socio-economic conditions.

**Materials and methods**

The designed system uses a generator charged with ammonia and water. The heat source is a solar radiation collector that collects and radiates solar thermal energy onto a black body generator. The collector is made of a composite walled box of section 50 cm by 40 cm (Fig. 1). The top section tapers from a height of 24 cm to the back wall of height 20 cm. This arrangement gives a declination angle of 6° corresponding to the angular position of the sun at noon in area where the research was carried out. Provision is made for altering the sloping angle of the collector surface depending on the region of utilisation. Two layers of glass separated by 5 cm of air space cover the box. The internal wall is lined with aluminium foil that reflects the heat onto the black body ammonia generator. During the generation cycle, the ammonia becomes vaporised and is driven off. The ammonia vapour at the top of the system is condensed by the air-cooled condenser into a saturated liquid. The liquid flows by gravity through a check valve into a liquid receiver. The liquid ammonia flows through a restrictor into the evaporator. The restrictor helps in controlling the rate of liquid flow to the evaporator thereby protecting the evaporator from getting flooded. The restrictor produces an expansion valve effect which creates a pressure differential. The pressure differential causes the liquid ammonia to change it’s boiling point from a high pressure flash of temperature to a lower pressure flash off temperature. When the source of heat, solar energy is blocked, the generator cools down causing the ammonia to evaporate at low temperature. The cooling effect of the evaporator causes a pressure drop, which makes the ammonia to boil absorbing heat. The vaporised ammonia is reabsorbed into the generator. Many generation cycles are possible in one day depending on the intensity and duration of solar insolation.
Figure 1. *Solar Refrigerator and its components.* (a) front view; (a) back view; (c) evaporator; (d) generator inside the collector chamber and (e) solar collector.
Determination of the refrigeration load

The refrigeration load \(Q_T\) was estimated using equation 1. This load is the quantity of heat that must be extracted per day from the refrigeration compartment [4, 5, 6, 8].

\[
Q_T = Q_g + Q_p + Q_i + Q_a
\]  

(1)

The heat gain to the system was estimated using power gain equation 2 as recommended by [5]:

\[
Q_g = UA\Delta\theta
\]  

(2)

and:

\[
Y = \frac{1}{\left(\frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_0}\right)}
\]  

(3)

therefore,

\[
Q_g = \frac{A\Delta\theta}{\left(\frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_0}\right)}
\]  

(4)

For this work, the thickness of the thermal insulator was taken as 0.03 m, the maximum ambient temperature at the zone of study is 29°C, the final temperature of the refrigerator was chosen to be 0°C, the values of \(f_i\) and \(f_o\) for the walls frequently used for still air is 9.37 W m\(^{-2}\)°C\(^{-1}\) [5, 9]. The refrigeration compartment is rectangular in section of width 0.63 m, length 0.50 m, and height 1 m. The total surface area \(A\) of the walls was therefore 2.89 m\(^2\). The value of \(K = 0.02833\) W m\(^{-2}\) °C\(^{-1}\)

Substituting all these values into equation 2 gave:

\[
Q_g = 66.0\text{ W and this is equivalent to 237.6 kJ per hour or 5688 kJ per day}
\]

The sensible heat \((Q_p)\)

The sensible heat of the produce was taken as the heat produced during respiration \((Q_{pr})\) and the heat removed to lower the temperature of the product to safe storage point \((Q_{ps})\)

\[
Q_p = Q_{ps} + Q_{pr}
\]  

(5)

1. Product cooling load \((Q_{ps})\)

A typical perishable product in the tropics, tomato, was used to estimate the total heat to be removed from the product during cooling. Equation 6 was used to estimate the value of this load.

\[
Q_{ps} = MC_3(\theta_3 - \theta_s)
\]  

(6)

The following values were chosen: \(M = 40\) kg; \(C_3 = 3980\) J kg\(^{-1}\)°C\(^{-1}\) ([10]); \(\theta_3 = 15\) °C; \(\theta_s = 0\) °C

Therefore \(Q_{ps} = 2388\) kJ.
2. Respiration load ($Q_{pr}$)

According to [10], the heat of respiration of tomato at 16°C is 492.3 J hour$^{-1}$ kg$^{-1}$°C$^{-1}$. Therefore 40 kg of tomato would dissipate 315.07 kJ per hour and about 7562 kJ per day. Between 0°C to 1.5°C tomatoes could be stored for up to three weeks [7]. After cooling to 0°C the heat of respiration is supposed to drop considerably but for design purpose, the value at 16°C was maintained.

$$Q_{pr} = 7562 \text{ kJ}; \quad Q_{tr} = 2388 \text{ kJ}.$$  

$$Q_p = Q_{pr} + Q_{tr}$$

Hence $Q_p = 9950 \text{ kJ per day}$

Air infiltration load ($Q_a$)

This was estimated using the equation of [4].

$$Q_a = QVE$$  \hspace{1cm} (7)

The value of $E$ chosen was 50, which is recommended for refrigerators that are frequently opened. The maximum humidity assumed was 80% and the design minimal temperature of the refrigerator is 0°C, therefore according to [4], the heat to be removed from infiltration air is 24,600 J m$^{-3}$. Substituting these values into equation 7, the infiltration heat load over twenty four hours period was obtained as $Q_a = 290.280 \text{ kJ}$.

The internal heat $Q_i$ is zero in this case.

The total refrigeration load per day is therefore

$$Q_T = (5688 + 9950 + 2388 + 290.28) kJ$$

$$= 18,316.26 \text{ kJ per day}.$$  

Determination of the quantity of the refrigerant

The system provides saturated ammonia liquid at 26°C/10.34 bar at condenser outlet. This liquid is then expanded as it enters the liquid receiver through a valve. The liquid now enters the evaporator at 1 bar / −33°C to provide the required cooling. The amount of heat absorbed by the evaporation process is

$$Q_e = h_{g(-33.4°C)} - h_{f(26°C)}$$  \hspace{1cm} (8)

$h_{g(-33.4°C)} = 1400 \text{ kJ kg}^{-1}$ and $h_{f(26°C)} = 303.7 \text{ kJ kg}^{-1}$ [11] and therefore $Q_e = 1099.3 \text{ kJ kg}^{-1}$ of ammonia. The required quantity of ammonia was obtained from equation 9.

$$M_a = \frac{Q_T}{Q_e} = \frac{18,316.26 \text{ kJ}}{1099.3 \text{ kJ kg}^{-1}} = 16.7 \text{ kg}$$  \hspace{1cm} (9)

Experience shows that when steady conditions have been reached, the refrigeration load reduces considerably and remains very low until a new charge is made to
the refrigeration compartment. Also if the number of generation cycles are increased from one, the quantity of the refrigerant needed initially would have to be divided by the number of cycles per day and this would end up reducing further amount of refrigerant needed. Hence the quantity of the refrigerant depends on the number of cycles per unit time and on the frequency of charging of the refrigeration compartment.

The number of insolation hours per day at the test site can range from 3 hours in July to about 10 hours in December.

**Design of the solar collector**

The design took into consideration the intensity of solar radiation in the area of study. A horizontal surface in Dschang in Cameroon in the month of July absorbs 300 cal cm$^{-2}$ per day (12,540 kJ m$^{-2}$ per day) [17]. It has been stated [18, 19] that a flat plate collector efficiency ranges between 0.50 to 0.67 due to heat losses and heat reflected away by the glass cover. An efficiency of $\eta_c = 0.60$ was assumed.

The following expression was used to calculate the surface area of the collector required.

$$S_c = \frac{Q_r}{E_i}$$  \hspace{1cm} (10)  \hspace{1cm} [12, 13, 14]

Considering the efficiencies of the collector and that of the refrigeration process (0.8 assumed in this case [20]), the equation was modified as follows:

$$S_c = \frac{Q_r}{\eta_r \cdot \eta_c}$$  \hspace{1cm} (11)

$E_i = 12,540$ kJ m$^{-2}$; $Q_r = 18,316$ KJ k, $\eta_c = 0.60$, and $\eta_r = 0.80$ and therefore $S_c = 3.0$ m$^2$

The collector was fabricated with a solar declination of 6° corresponding the latitude of this region. This means that a surface inclined at 6° to the horizontal will receive solar radiation at right angles at noon when the sun is overhead. However, provision was made for variation of this angle of tilt depending on the region of utilisation. At this time the intensity of solar radiation is highest if there is no cloud cover.

**Liquid receiver**

This is made of mild steel plate, rectangular in section with the following dimensions: $(200 \times 100 \times 100)$ mm. It is recommended [4] that the volume should be at least 15% larger in size than the total volume of the refrigerant. Between the liquid receiver and the evaporator is a restriction that serves in reducing the pressure of the refrigerant in the evaporator. This restriction also serves in extending the length of the cooling period.
The generator

It was fabricated with 1 mm thick mild steel plate and painted black to improve on its solar radiation absorbing capabilities. The section is rectangular and the dimensions are 20 cm × 10 cm by 10 cm. The volume is 2 litres. Mild steel was used because other nonferrous materials like copper and brass are attacked by ammonia. Above it there are two pipes one for the liberation of the refrigerant vapour to the condenser and the other to absorb the refrigerant. The pipe bringing back the refrigerant after circulation dips into the ammonia water mixture and therefore enhances the absorption process. Another small hole located at the side is for the refilling of the ammonia and the absorbent, water in this case. The quantity of water used is 0.35 L.

Performance evaluation

The constructed refrigerator was placed outside under solar radiation and temperatures were monitored at the floor (θ₆), on the side (θ₇) and on the evaporator (θ₅). The temperature sensors were thermocouple (Constantine/Copper) wires fixed with a tape at the measuring point. Another sensor was placed outside the refrigerator to read ambient temperatures (θ₁). With this arrangement it was possible to read temperatures at various points inside the refrigeration compartment without opening the lead.

In the absorber thermocouple wires were installed at two points θ₂ and θ₃. In the refrigeration chamber the thermocouple wires were installed at three points: on the top, on the floor and on the wall midway between the floor and the roof. Temperatures at various points were monitored at intervals of 6 hours during a period of 24 hours with an electronic thermocouple register. Initial tests were for one generation cycle during the insolation hours of each day.

The coefficient of performance COP was estimated by taking the ratio of the cooling effect to the heat supplied to the system [21, 22]. In practical terms this was the ratio of the total energy absorbed at the evaporator in a day to the heat supplied to the generator in a day [23].

\[
COP = \frac{Q_r}{E_r S_c}
\]  

\[
COP = \frac{18,316.26 \text{kJ}}{12540 \text{kJ m}^{-2} \times 3 \text{m}^2} = 0.487
\]

Results and discussions

Table 1 shows average temperature variations in the refrigeration compartment (θ₆), the generator (solar collector) (θ₅), and in the atmosphere (θ₆) at the time of test. Between 10 am and 2 pm, we have the highest atmospheric and collector temperatures. The average peak atmospheric temperature at 12 noon is 25°C and the peak collector temperature is 100°C. The average lowest temperature of the solar collector is 21°C because from 17 hours till dawn, there is no solar radiation. This is normal
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for absorption refrigeration systems because the absorbent: water, has to cool down in order to absorb the ammonia that is vaporised in the evaporator for the cooling to take place.

It can also be seen that the average refrigeration temperature varies with time, the minimum being 4.4°C at midnight. This temperature increases and attains it maximum at 11.3°C at noon because the ammonia is mostly vapour form and is condensing and also because of considerable cabinet heating from solar radiation. When the heat source is removed and the absorbent cools down, the vapour now starts moving back into the generator.

Fig. 2 shows the average temperature variation at three points in the system: the refrigeration compartment, the solar collector (generator) and the ambient temperature. It can be seen that refrigeration temperatures are lower than ambient and generator temperatures. All the valves are opened during operation. Refrigeration does not take place during generation because the generator is relatively warmer and cannot absorb the ammonia vapour. As soon as the system is deprived of solar radiation, the collector starts to cool down absorbing the ammonia vapour from the evaporator and thus ensuring fluid flow. The restriction valves in the evaporator make the ammonia to flow very slowly insuring a longer time cooling effect. The schematic representation of the three main parts of the system is shown on Fig. 3.

The refrigeration compartment remains below 10°C during the generation process because of little heat gain after the previous day’s cooling activities. It is important to note that the test were carried out with the refrigeration compartment always closed. Temperatures at various points inside the system were monitored with thermocouple sensors placed inside the closed compartment. Because of this the air infiltration load could be assumed to be minimum. Under practical situations,
as the compartment is opened and closed, the temperatures inside will definitely rise.

The average peak temperature in the solar collector is about 100°C. Although this is quite high it is a little bit lower than values reported in this region for solar collectors built for water heaters and incubators [16]. The reason is that for this small refrigeration plant, the solar collector is quite small compared to the ones used for other purposes. It was not possible to achieve the designed evaporator temperatures of 0°C. This could be explained by the fact that standard design equations carry a lot of assumptions and may deviate from practical realities. Also the climatic data taken from maps and tables are only averages which may have considerable deviations at short periods.

The problem noticed with the system is that there is considerable cabinet heating by solar radiation when the system is placed outside the building. It might therefore be good to design systems that would locate the solar collector outside a building and the refrigeration compartment inside a building. Also since the system is intermittent, the solar collector will have to be shielded from solar radiation when all the ammonia has been vaporised and this will demand extra labour. Where available it is recommended that such systems be incorporated with green house solar roof venting mechanism for mechanical opening and closing of the collector. The COP for the system was evaluated as shown above to be 0.487. Although this value is small it compares favourably with values reported for similar systems [23, 24, 25, 26, 27].

Figure 2. Average temperature variation at various points in the solar refrigerator.
Conclusions

A solar energy powered refrigeration system was designed, fabricated and tested. The lowest average temperature obtained in the system was 4.4°C and the highest temperature obtained was 11.3°C, which is still far below the average lowest atmospheric temperature of 16°C. The coefficient of performance of the system 0.487. Although the system is not very efficient because of the low COP, it can be conveniently used to store medicinal products and fresh foods. However, there are still some problems regarding its management. This includes the necessity to shield the collector from solar radiation at the end of the generating cycle and the necessity to shield the refrigeration cabinet from solar radiation that tends to add more heat to the system.

References