Solar Powered Intermittent Absorption Refrigeration Unit

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ABSTRACT

The study investigated and evaluated the feasibility of an absorption refrigeration unit on solar power. Its effectiveness as a viable refrigeration option for use in household refrigerators or as an energy efficient and environmentally friendly alternative to conventional refrigerated air conditioning units used in the offices are evaluated. A prototype model that is capable of producing a temperature change in the evaporator was designed, fabricated and tested. A parabolic solar trough was used as a source of heat gain. The model utilized the technology of an intermittent absorption refrigeration system. The performance and effectiveness of the unit was studied by determining refrigeration effect (RE), coefficient of performance (COP) and explaining operational issues of the unit. The ultimate goal in the long term would ideally be to reduce the consumption of electricity used for refrigeration and air conditioning, hence saving money and reducing the stress on our electricity generation and distribution networks.

1. INTRODUCTION

As the world becomes more self aware of the changing climatic conditions caused by global warming it is vital to reassess our dependence on the burning of fossil fuels to gain energy [1-5]. The alternatives for gaining this energy can be found in the sources of renewable energy such as solar, wind, biomass, wave and tide, etc. [6, 7]. In particular, the solar energy alternative is now being more closely examined in an attempt to utilize this as a source of energy for both domestic and commercial end users such as refrigerators, air conditioners, hot water heaters, desalination for water recycling, etc. [8, 9]. In this study, the adoption of solar energy as the primary source of power for an intermittent absorption refrigeration system is investigated. The design, fabrication and testing of such a system is presented and discussed. The performances and effectiveness of the unit as household refrigerators is analyzed. Operational issues, suitability and problems of the unit are discussed.

2. ABSORPTION REFRIGERATION SYSTEMS

The basic operations of an absorption refrigeration unit involve freeing the refrigerant from its bonds with the absorbent material and then condensing it under pressure

[10-14]. This liquid refrigerant is then evaporated by reducing its pressure in turn absorbing heat from its surroundings and creating cold. This cold is called refrigeration effect (RE) which is achieved in the evaporator. There are two distinct types of absorption refrigeration units these are the intermittent and continuously operating systems [10, 11]. In intermittent operating system, the heat is only applied to the generator of the system once per day. The application of heat separates the refrigerant from the absorbent, condenses it and then the liquid refrigerant is stored. These systems operate at a single pressure which self regulates the condensation and evaporation rates of the refrigerant. Once the internal pressure of the system drops below the vapor pressure of the refrigerant it begins to evaporate. This in turn increases the system pressure until the refrigerant combines again with the absorbent material. The stored refrigerant usually produces a cooling effect for approximately 12 to 18 hours at which stage more heat is applied to the generating unit.

The basic operating principals of continuously operating absorption refrigerators are the same as the intermittent with the exception of the critical components allowing the system to run on a continuous basis powered by a heat source such as gas/solar/kerosene, etc. The configuration of a continuous system involves the generator, condenser and evaporator the same as an intermittent system but also incorporates an absorber positioned between the evaporator and generator. This additional component allows the refrigerant to recombine with the absorbent while the generator continues to operate. A bubble pump which resembles a coffee percolator is also used in most designs to transport the weak absorbent from the generator to the absorber to receive refrigerant which has completed the circuit. This type of system also requires the use of hydrogen. This element is located in the evaporator and helps the ammonia vaporize increasing the efficiency of the system.

The absorption refrigeration systems have lower COP compared to that of a vapour compression system. The COP of absorption refrigeration system can be determined by [14].

\[
COP_{abs} = \frac{\text{refrigeration effect}}{\text{rate of heat addition at generator}}
\]
3. EXPERIMENTAL

3.1 Experimental Set-up (Prototype)

The prototype systems designed in this study was similar to that used by Vanek et al. [15] for solar thermal icemaker. The layout of the system was very simple involving only three main components being the combination collector generator for heating the salt-ammonia mixture, condenser coil in water bath and an evaporator where distilled ammonia collects during generation as shown in Figure 1. This system used a parabolic trough collector to heat a tube at its focal point. This tube formed the generator for the absorption system giving it direct heating from the sun.

![Layout of the Solar Thermal Icemaker](image)

Figure 1: Layout of the Solar Thermal Icemaker Used by Vanek et al. [15].

Anhydrous ammonia and calcium chloride salt was used as refrigerant and absorbent material respectively in this study. Ammonia is very reactive to certain metals which should not be used as part of a refrigeration unit. Research has shown that ammonia, especially in the presence of moisture, reacts with and corrodes copper, zinc, and many alloys. Only iron, steel, certain rubbers and plastics, and specific nonferrous alloys such as stainless steel resistant to ammonia were used for the design and fabrication of the system. Another "must" design feature is the ability for the system to hold pressure. Upon vaporization ammonia expands greatly and produces high pressure in enclosed systems. Any refrigeration system using ammonia must be capable of holding pressure in excess of 1380 kPa without leaks or rupture. The fabrication and construction of the system was kept as simplistic as possible. The use of specialized tools was kept to a minimum therefore reducing the final cost of construction. The assembled unit is shown in Figure 2. The following design conditions were applied in order to fabricate the experimental set-up:

- The size of the parabolic mirror and framework as well as collector tube were kept to a minimum practical size, which was based around the size of a full sheet of mirror available in the market of size 1220 x 2440mm.

This was done mainly to reduce the construction cost and an estimation was made that one sheet would provide adequate surface area to generate the necessary heat to run a relatively small system. All the piping and fittings used in the system were capable of withstanding a constant minimum pressure of 1400 kPa.

- The condenser tank was positioned in such a way that the outlet of the collector tube was below the outlet of the condenser coil. This would force the hot ammonia into the condenser. An old hot water tank was used so that a more accurate temperature change could be recorded due to the surrounding insulation and glass coating on the tank retaining the heat in the condenser water. Recording the temperature change would provide the means to perform an energy gain calculation and to discover what energy was lost by the ammonia and maybe how hot it was upon exiting the collector tube. The condenser was also positioned in such a way that it would not impede the sun's rays contacting the mirror were the sun was. The size and specifications of the condenser coil was similar to that used in the intermittent solar icemaker by Vanek et al. [15].

![Assembled unit ready for testing](image)

Figure 2: Assembled unit ready for testing

- The frame supporting the condenser tank has been designed so that the majority of the weight would be placed on the main support structure through two legs. The third leg was placed on an outrigger to provide balance for the structure as well as additional support for the estimated 200kg mass of the condenser tank once filled. The frame was also made to be removed for disassembly and transportation purposes.

- The entire unit was placed on a single frame for easy transport site to site. Wheels were attached to the frame to allow easy short range
3.2. Experimental Procedures

The experiment was conducted in order to observe and record temperature of different components of the unit and systems pressure which allows calculation of RE and COP of the unit. The prototype was tested in two ways. The protocol for the Test 1 involved the system collector being aligned East-West and facing North. The mirror then was tilted to align with a median position of the suns inclination during the hottest part of the day approximately 10:00 to 14:00hrs. No other tracking of the sun was done during this testing period. The Test 2 was involved tracking the sun in 15 minute intervals both in its inclination and trajectory across the sky. This provided greater exposure of sunlight normal to the mirror surface. This light applied directly to the collector tube and not be deflected away at certain times of the day as in the case of Test 1. On both the tests the collector tube temperature, the temperature at the condenser inlet, the condenser water temperature, the temperature at the condenser outlet, the system pressure and the evaporator temperature were observed and recorded.

The system in operation during Test 1 is shown in Figure 2. The system begins its cycle during the day when the system mirror is directed to the sun. All the light striking the parabolic mirror is redirected to the collector tube in order to heat-up the tube. This heat is applied to the absorbent/refrigerant combination throughout. The heat releases the refrigerant as a gas which rises and makes its way to the condenser. For simplicity of manufacture, the condenser was taken as water cooled meaning that only a coiled tube was necessary. Due to the increased system pressure the refrigerant can be condensed at the temperature of the water. The liquid refrigerant travels under gravity to the refrigerant receiver located in a fridge compartment. This process was continued throughout the day until the heat being applied can no longer release the refrigerant.

After the sun sets the temperature and the pressure in the collector tube reduces, and the refrigerant begin to boil. Refrigerants boil at much lower temperatures than most of the other liquids and therefore draw energy from the surroundings and produce cold. The boiling refrigerant returns to a gaseous state and can be returned back to the generator to be reabsorbed ready for the next day. It is this process which gives the intermittent refrigerator its name the process of heating and cooling occurs in different stages where a continuous cycle requires heating on a continuous basis in order to maintain a constant cooling effect.

4. RESULTS AND DISCUSSION

4.1. Observation in Test 1: Non-Sun Tracking

The experiment was initiated at approximately 10:30 am. The mirror was wheeled outside and aligned East–West and facing North, it was then tilted to align with a median point of the inclination between the start time and the midday point. Temperature of the collector tube, at the condenser inlet, condenser water, at the condenser outlet and evaporator were recorded using thermocouple and digital monitor. Figure 3 shows these temperatures.

It was at this time the sound of pressure being released was heard. It was also at this point when the evaporator was observed to decrease in temperature to the point where condensation formed on the refrigerant receiver and cooling coil. The temperature was recorded as around 6 °C. The fact that the evaporator became cold leads us to believe that the release of pressure was from the condenser to the collector. The pressure gauge had read approximately 840 kPa at the time of release and reduced to 280 kPa. The evaporator did remain cold for some time until the pressure inside the system rose to a point at which the boiling of the refrigerant would have ceased. The evaporator temperature then rose to a point which was close to ambient (24.5 °C). The measurements were taken at intervals of 15 minutes. This was done because the acquisition and recording of all the necessary temperature, pressure and electrical readings took approximately 7 to 10 minutes to achieve. The system pressure and collector temperature reached a maximum at 13:00. The maximum pressure was 930 kPa and the maximum collector tube temperature was 129 °C.

![Figure 3: Temperature profiles of different components during Test 1](image)

Clouds played a major part in the reduction of heat to the system. By observing the pressure and temperature readings at times where the sun had been covered by a
cloud for some time there were noticeable drops in system pressure as the temperature of the collector tube dropped. As much as clouds are annoying they are always going to be a variable in any solar experiment. It is therefore necessary to take them into account when designing a collector. At around 2pm due to cloud and a non direct angle being struck on the mirror, less heat was being transferred to the collector tube. This in turn began to decrease the temperature and pressure of the system. It was at this point that the temperature in the evaporator also began to decrease. From its maximum point of 24.5 °C it dropped to a minimum of 3 °C by 16:45 hours. Unfortunately, after this point the temperature again began to rise. This could be due to either the increase of the system pressure or the saturation of the absorbent material.

During the cooling phase and the re-absorption of the vapor ammonia by the calcium chloride a similar phenomenon was observed as was seen during the charging of the system. This phenomenon was the chemical induced heating of the collector tube as the ammonia and calcium chloride combine. This was shown in the collector tube surface temperatures at different areas along the pipe. It was seen that the area a quarter of the way from the T intersection was the hottest region of the collector. This is the area where the ammonia gas is making contact with the absorbent material and creating a chemical reaction. This type of reaction is seen in all absorption systems, however, it is usually the task of the absorber to reject the heat produced during the reaction so that absorption can continue at an acceptable rate.

4.2. Observation in Test 2: Sun-Tracking

Figure 4 shows the temperature recordings of the components. During this test the sun was tracked on a 15 minute basis using a sun dial to align both mirror inclination and rotational position and was done at the same time as instrument readings were taken. The amount of direct sunlight was a big factor in the operation of the system. Cloud cover was observed from approximately 10:45 in the morning to after midday with small breaks of approximately one to two minutes. Due to this the collector tube was not receiving the constant energy input required to sustain high temperatures and subsequently large temperature drops were recorded during the hottest part of the day. Once the surface temperature dropped to a level between 60 and 80 °C it was able to be sustained with the available sunlight input. This shows that this collector despite its imperfections was able to concentrate the minimal sunlight available and use it to sustain a reasonable temperature in the collector tube.

The initial pressure recorded for the day was 770 kPa. This appeared a lot higher than expected. The high pressure indicates that a large portion of the ammonia was not reabsorbed into the calcium chloride sustaining the high pressure. The system pressure did rise during the day however did not seem to correspond very closely with that of the Test 1. For example, in Test 1 the system pressure peaked at 945 kPa when the temperature peaked at 129 °C. The similar peak did occur on this occasion however it was a much lower pressure for the collector temperature reached. The maximum pressure corresponding to the maximum temperature of 141 °C was approximately 860 kPa. This does not seem relative.

![Figure 4: Temperature profiles of different components during Test 2](image)

4.3. The COP and Operational Issues

In test 1, the minimum evaporator temperature reached was 3 °C which is reasonable. The collector tube reached a maximum temperature of 129 °C which is quite high considering the complexity of the mirror design and thickness of the collector tube. In test 2, the minimum temperature reached was 17 °C. This was due to the re-absorption process or lack of maintaining a high system pressure and therefore reducing the evaporation of the refrigerant and preventing low temperatures. The temperature of the collector tube however was recorded much higher due to hotter sun in the first 2 hours of day two with a temperature of 141 °C. The enthalpy value of saturated vapour (outlet of evaporator) and saturated liquid (outlet of condenser) were taken from Mollier diagram for ammonia (pressure-enthalpy chart). Figure 5 shows pressure – enthalpy diagram for Test 1, item 1 only. Similar diagrams were drawn for other items of the measurement. The conversion of the Pyranometer reading to a kW value was done considering 144 mV = 1 kW i.e. for every 144 mV of reading on the multi-meter means that 1 kW is being collected for every square meter of parallel collector surface area. This is of course the best case scenario and an efficiency factor need to apply to this figure to obtain actual energy input to the collector tube. The collector conversion efficiency was assumed as 20% as found by Rasul et al. [9]. The input power was calculated using the formula given below,

\[
\text{Input Power} = \frac{\text{Pyranometer reading}}{144} \times \frac{\text{mirror surface area}}{\text{collector efficiency}}
\]
The enthalpy readings, RE and COP calculations for the systems during both the tests are given in Table 1.

![Figure 5: Mollier (p-h) diagram for ammonia](image)

Table 1: The enthalpy, RE and COP calculation

<table>
<thead>
<tr>
<th>Tests</th>
<th>$h_1$ (kJ/kg)</th>
<th>$h_2-h_1$ (kJ/kg)</th>
<th>Mass flow rate (kg/s)</th>
<th>RE = $\frac{h_1-h_2}{h_1}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>520</td>
<td>-580</td>
<td>1.85 x $10^{-4}$</td>
<td>0.204</td>
</tr>
<tr>
<td>Test 2</td>
<td>537</td>
<td>-610</td>
<td>6.96 x $10^{-4}$</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 1: The enthalpy, RE and COP calculation (cont.)

<table>
<thead>
<tr>
<th>Tests</th>
<th>Pyranometer reading (mV)</th>
<th>Power input (kW)</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>92</td>
<td>0.312</td>
<td>0.65</td>
</tr>
<tr>
<td>Test 2</td>
<td>85</td>
<td>0.305</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The COP of 0.65 found in Test 1 seems reasonable [13], although the system was not operating to the best of its ability. In Test 2, the system operated very badly which produced COP of 0.26 because the evaporator temperature could not go below 17 °C which has contributed to a lower COP. Although the results are encouraging, there are rooms for improvements to be made in order to make the system produce more usable conditions. The system is easy to use and incorporates no complicated control systems instead relying solely on the changes in system pressure to control the outputs.

In its current form the device would not be considered applicable for use in a modern home or office. However, the applications for this particular system could be in remote areas where adequate refrigeration is not available to stop perishables such as meat and medicines from going off and where electricity is not readily available from main supply, particularly remote areas in third world countries. As for the developed world, a system which could be installed in a household or office will require additional development to achieve but is definitely not impossible to accomplish.

A modification would need to be made to the device to give the calcium chloride greater surface area during the re-absorption or cooling phase of the process to avoid the cooling problem observed in Test 2. This could be achieved by introducing a perforated tube through the centre of the collector tube. The calcium chloride would then be re-packed around the tube leaving a hollow space the entire length of the collector tube. The surface area allowed for the ammonia to be reabsorbed into the calcium chloride will then be greatly increased. By providing extra surface area and hence extra absorption rate, the rate of refrigerant boiling can be increased, decreasing the evaporator temperature.

The second option would be to use water as the absorbent due to its great affinity with ammonia. However a problem exists with this option being that the collector tube is capable of temperatures in excess of the boiling point of water. If water is vaporized in the current system it would be condensed and run into the evaporator. Any water in the evaporator of an ammonia absorption system is a bad as the two will recombine trapping the ammonia not allowing it to boil and produce cold. The only way to stop the water reaching the evaporator is to condense it before it reaches the main condenser. This would be done with a pre-cooler constructed and positioned so that the condensed water would be gravity fed back to the collector tube ready for the re-absorption of the boiling ammonia during the night cycle. The design of a pre-cooler will be easier because the temperature and pressure measurements have already been done during the testing of the original system. There are two possibilities for its construction being water cooled and air cooled. Both would perform well due to the pressures experienced in the system which would increase the boiling temperature of the water and therefore the temperature at which it also condenses.

5. CONCLUSIONS AND RECOMMENDATION

The prototype system tested in this study performed fairly in order to achieve the goals of the study. However, modification and further testing would be necessary before the system is capable of performing a worthwhile duty. In order to improve the system it is
recommended that the re-absorption process be studied further so that a lower evaporation pressure and therefore temperature may be reached. This will involve increasing the absorbent surface area and possibly also investigating alternative dry and wet absorbent materials.

REFERENCES