Science Journal of Energy Engineering
2019; 7(1): 1-12
http://www.sciencepublishinggroup.com/j/sjee
doi: 10.11648/j.sjee.20190701.11
ISSN: 2376-810X (Print); ISSN: 2376-8126 (Online)

Methodology Article

Design and Analysis of a Solar Driven Vapour Absorption Refrigeration System as an Alternative to Solar PV Powered Refrigerators

Ogbonda Douglas Chukwu*, Fubara Ibinabo, Raphael Okosiemiema

Department of Electrical Electronics Engineering Technology, School of Engineering Technology, Captain Elechi Amadi Polytechnic, Port Harcourt, Nigeria

Email address:
ogbonda.chukwu@gmail.com (O. D. Chukwu)
*Corresponding author

To cite this article:
Ogbonda Douglas Chukwu, Fubara Ibinabo, Raphael Okosiemiema. Design and Analysis of a Solar Driven Vapour Absorption Refrigeration System as an Alternative to Solar PV Powered Refrigerators. *Science Journal of Energy Engineering.* Vol. 7, No. 1, 2019, pp. 1-12.
doi: 10.11648/j.sjee.20190701.11

Received: March 11, 2019; **Accepted**: April 26, 2019; **Published**: May 20, 2019

Abstract: There exists an immense need around the world for refrigeration capabilities where the infrastructure of dependable power does not exist. In this study, the concept of a flat plate collector for an intermittent ammonia absorption refrigeration system is analyzed. The design is juxtaposed against a solar photo-voltaic powered refrigerator to evaluate its feasibility. Relevant design equations, codes, standards and procedures were integrated to develop a system that would boil off approximately 0.34kg of ammonia from 0.553kg of calcium chloride capable of producing 0.91kg of ice. The results showed that a collector area of 0.93m^2 was needed to produce the 782.4kJ of heat required, the required condenser volume was calculated to be 28.4 liters, and the evaporator volume to hold the ammonia calculated to be 0.51 liters (Length = 0.4 m, D = 40 mm). The copper fin – steel pipe stress due to thermal expansion of the system was calculated to be 59.159 MPa which was below, 249.944 MPa, the maximum allowable stress of the material. The system was designed to have a maximum operating pressure of 9653 kPa. In a test, the final prototype attained consistent generator temperatures in the 364 - 378K range and once switched to the "night cycle" attained evaporator temperatures in the 0°C to -7°C range thus confirming the concept of the flat design (the primary objective) as well producing consistent evaporator temperatures below 0°C (the secondary objective).

Keywords: Refrigeration, Ammonia, Calcium-Chloride, Flat Plate Collector, Condenser, Evaporator

1. Introduction

Economically speaking, the importance of refrigeration is paramount. Refrigeration is vital for reducing post-harvest and post-slaughtering losses and in the preservation of food products. As refrigeration maintains food safety, nutritional and organoleptic qualities, it has become fundamental for the retail sector. Along with refrigerators and freezers, air conditioners are now an essential part of our daily life. In the healthcare sector, refrigeration preserves pharmaceuticals and medicines, especially vaccines [1]. Powered by means of electricity and capable of cooling by means of chlorofluorocarbon refrigerants (CFC), refrigerators also emit CO_2 thus contributing to the "Greenhouse Effect" dilemma we are currently faced with today. Fluorocarbon refrigerants (such as R-134a or R140a) are found not only in refrigerators, but air conditioning units as well. It is estimated that about 1 kg of refrigerant emissions is equivalent to two tons of CO_2 emissions [2].

In Sub Saharan Africa, refrigeration capabilities remain deficient, largely due to the limited power supply still plaguing large parts of the continent. Access to modern energy services, though increasing, remains limited: despite many positive efforts, more than 620 million people in sub-Saharan Africa remain without access to electricity and nearly 730 million rely on the traditional use of solid biomass for cooking. Electricity consumption per capita is, on average, less than that needed to power a 50-watt light bulb continuously. About 80 percent of those without electricity live in rural areas, away from the grid. So at first glance, it might seem like this problem will take care of itself as more people move to cities. But the International Energy Agency (IEA) notes that, unlike other parts of the world, Africa is actually expected to see its rural population grow in the coming years [3].

In Africa, a large number of people live on one dollar per day. Small-scale rural farmers go through extraordinary lengths transporting fresh produce from rural areas to marketplaces. The sun is scorching and is harmful for the produce leading to some financial losses, perpetuating an unending cycle of poverty in developing countries [4]. A striking example is India where less than 4% of the country's fresh produce is transported under low-temperature conditions, as compared with over 90% in the UK [5]. This results in huge food waste and economic losses. According to the International Institute of Refrigeration (IIR), the lack of a cold chain causes significant global food losses: up to almost 20% of the global food supply. In developed countries, food losses from the absence of refrigeration account for nearly 9% of the total food production, and 23% on average in developing countries [6]. Some households, unable to store leftovers, also incur losses through wastage and are unable to afford subsequent meals. The Food and Agriculture Organization of the United Nations (FAO) estimates that food production will have to increase globally by 70% (about 4,400 million tonnes) to feed an additional 2.3 billion people by 2050 and refrigeration has a vital role to play in this context [7]. Refrigeration can also make a significant contribution to addressing the issue of undernourishment, especially in the least-developed countries. Setting up of cold chains for perishable foodstuffs, which are as extensive and reliable as those in industrialized countries, would enable developing countries to raise food supply by about 15% (i.e. about 250 million tonnes) [6]. Solar driven refrigeration could prove to be a useful tool to plugging the shortfalls of refrigeration needs in off-grid areas.

Solar ice makers use the sun's energy to run an intermittent solid adsorption cycle to produce ice. Unlike a refrigerator or freezer, this device requires no electricity whatsoever and depends solely on a natural source of energy. Instead of using pollutant emitting refrigerants, solar ice makers use environmentally friendly substances such as ammonia and calcium chloride [8]. The solar ice maker uses an "adsorption process" rather than a "refrigeration process." During the daytime, a solar collector panel reflects sunlight on the generator. The generator then absorbs the energy and the ammonia within is boiled into the condenser forming a liquid. In then flows into the evaporator where it is evaporated by the decrease in outside temperature, as the day turns into nightfall. Water forms and is then frozen into ice as the temperature drops below 0°C. The evaporated ammonia is then cycled back into the generator.

Vanek et al (1996) Solar Ice Maker team built a flat plate collector device much like existing solar driven absorption devices [9]. This device featured a single generator section and was able to produce approximately 1.50kg of ice. Unfortunately, the device had leaks in the system that may have facilitated the generation of ice. The data from the last test showed that pressure in the system was decreasing quite rapidly during the ice-generating "night cycle" of the device. This indicated that the leak in the system allowed the pressure to decrease and ultimately allowed the ammonia to evaporate in a premature manner. Ideally the pressure would remain fairly constant or decrease slowly as the evaporator temperature decreases.

1.1. Background

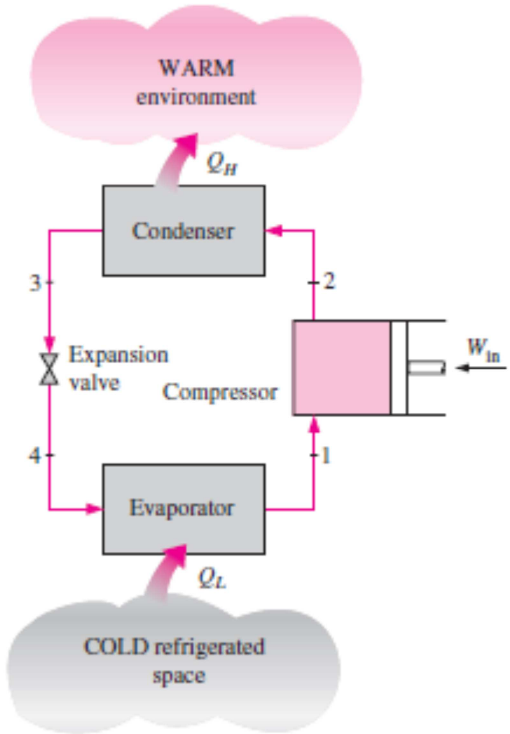

Figure 1. *Vapor compression cycle [12].*

The most common type of air conditioning utilizes the conventional vapor compression cycle. Vapor compression dominates the refrigerator and freezer industry because of its low cost of manufacturing and basic plug and play properties. Only a power source, typically an electrical hookup from the energy grid, is needed to operate the unit. Compressors typically cost an average of $100 to produce, and lasts approximately 15-20 years without failure. A vapor compression cycle consists of four processes. As seen in Figure 1: State 1-2 is refrigerant vapor compression, State 2-3 is the heat removal of refrigerant before entering expansion valve, State 3-4 is through the expansion valve where a pressure drop condenses the refrigerant, State 4-1 is the liquid refrigerant removing heat from cold space. The evaporator section absorbs heat from the cold space and removes it through the condensing section. Vapor compression cycles typically use chlorofluorocarbon (CFC), hydro chlorofluorocarbon (HCFC), and hydro fluorocarbon (HFC) based refrigerants. However, other refrigerants are being investigated, since these refrigerants are being slowly phased out due to its harmful impact to the environment [10].

On another note, there are other processes to refrigerate besides the vapor compression cycle. Other methods are, but not limited to, solar mechanical refrigeration and absorption refrigeration. Solar mechanical refrigeration, as Zeyghami et al explains, uses a conventional vapor compression system driven by mechanical power that is produced by a solar driven heat cycle. A Rankine cycle provides heat by heating a fluid to its vapor point through solar collectors. The heated vapor then powers a turbine or piston to produce mechanical power [11]. These systems can be very costly considering that efficiency increases with increased fluid temperatures exiting the solar collectors. This would mean more rugged construction, as well as a solar tracking system to follow the movement of the sun.

1.2. Solar Photovoltaic Hybrid Icemaker

The first automatic commercial PV ice-making system used to serve the fishing community of Chorreras, Chihuahua, Mexico [13]. This system allows the fishing community to receive ice to store preserve fish after the catch. The system uses solar photovoltaic panels to power a used commercial icemaker which was converted specifically for this application. As Figure 2 shows, the huge size of collection area is overwhelming.

1.2.1. Components

The components of this system are small and few. There is the 2.4kW PV array fixed at a tilt angle of 30 degrees. This PV array area measures an astounding 20.3m^2. The two 3.6kW inverters convert the sun energy into 240-vac to power the icemaker.

1.2.2. Operation

This hybrid icemaker is capable of making between 25 and 75 kg of ice per day; however, the total ice making capacity is rated at 400 kg per day with the use of a 6.3kW backup propane generator. There is a battery storage system that stores the energy during the day, since the used commercial icemaker requires 140-adc to operate. The PV array can only provide a maximum of 70-ADC. The icemaker runs at night to create ice for harvesting in the morning.

Figure 2. *Solar PV Hybrid Icemaker [13].*

1.3. Solar Driven Intermittent Absorption Icemaker

Absorption refrigeration, which the solar powered icemaker is based on, is similar to solar mechanical refrigeration except that absorption refrigeration relies more heavily on an adsorbent and refrigerant pair to refrigerate [14]. No electricity is required; only a heat source is needed. This is a good application in many situations where there are excess amounts of heat available. In many co-generation power plants, waste exhaust heat from the combustion process is used to operate absorption chillers. These absorption chillers can use lithium bromide and water, or water and ammonia as the working absorbent refrigerant pair. A need for cold storage in rural areas would be very difficult using conventional vapor compression systems which require electricity. Thus, this is an ideal situation to employ absorption refrigeration in places with plenty of sun radiation.

The solar powered icemaker uses a refrigerant and absorbent (ammonia NH_3 and calcium chloride $CaCl_2$) to create ice. The basic process is to combine the ammonia and calcium chloride together initially, and then using the sun's energy to separate the ammonia away from the absorbent. The separated ammonia vapor then flows through the condenser and down to an evaporator reservoir where the liquid ammonia collects. During the second half of the process at night, the pressure inside the system dips low enough under 20 psig, that the boiling point of liquid ammonia can be reached. At this point, the liquid ammonia boils, and in essence, absorbs heat from the surrounding space. It then travels back through the condensing section to the absorbent ready for to begin another cycle. This process is an intermittent process because it operates on a day and night cycle.

In conventional vapor compression systems, the refrigerant is pumped via a compressor through the cycle. In the intermittent absorption cycle, the flow of ammonia depends on the flow of heat and calcium chloride's absorbent properties. There is no need for a compressor in this process. The components in a solar absorption process is the generator for collecting heat, the condenser for removing heat, and the evaporator for removing heat.

Anhydrous calcium chloride is a salt typically used for deicing driveways and roadways covered with ice. It naturally absorbs water, and in doing so, creates an exothermic reaction releasing large amounts of heat. Calcium chloride also absorbs ammonia, which is ideal for this application. The absorbent helps attract the ammonia vapor back into the generator section during the night time cycle when creating ice.

Since anhydrous calcium chloride is a natural water absorbent it must be kept in a humidity controlled environment. If moisture is absorbed by the calcium chloride pellets, then this impedes the calcium chloride's ability to absorb ammonia once in the system. Water will hinder the thermodynamic properties of ammonia, so both calcium chloride and ammonia must be kept free of moisture [15].

Table 1. *Properties of common liquids [16].*

Boiling data at 1 atm		
Substance	**Normal Boiling Point, °C**	**Latent heat of vaporization hfg, kJ/kg**
Ammonia	-33.3	1357
Argon	-185.9	161.6
Benzene	80.2	394
Brine (20% sodium chloride by mass)	103.9	---
n-Butane	-0.5	385.2
Carbon dioxide	-78.4	230.5 (at 0°C)
Ethyl Alcohol	78.6	855
Kerosene	204 – 293	251
Mercury	356.7	294.7
Methane	-161.5	510.4
Nitrogen	64.5	1100
Octane	-195.8	198.6
Oil (light)	124.8	306.3
Oxygen	-183	212.7
Petroleum	---	230-384
Propane	-42.1	427.8
Refrigerant-134a	-26.1	217
Water	100	2257

From table 1, it is evident that water has the highest latent heat of vaporization. However, ammonia's latent heat of vaporization of 1357 kJ/kg is closest to that of water. Also from looking at table 1, it is clear that ammonia's high latent heat of vaporization is approximately six times that of refrigerant R-134a commonly used in vapor compression cycles. Ammonia's low boiling temperature -33.3°C is below the freezing point of water [17]. These two properties of ammonia make it ideal for refrigeration systems.

2. Methodology

The primary objective of this study is to prove the concept of a flat plate collector for an intermittent absorption refrigeration system as an alternative to a solar photovoltaic hybrid system. The processes include the design and analysis of a flat plate collector that is capable of boiling off ammonia present in calcium chloride to produce a significant temperature change in an adjacent evaporator. The secondary objective is to achieve an evaporator temperature of below 0°C while staying within the financial constraints inevitably imposed.

The improvement of the Vanek et al [3] solar icemaker team's design begins with calculations to determine sizes for all the general components of the icemaker. These components include but are not limited to: chemical ratios, collector, generator, condenser, and the evaporator. However, to begin with, calculations are done to check if a solar PV hybrid system could be a better more practical way to make ice.

2.1. Functional Specifications

The system will be a solar driven intermittent absorption refrigeration system having a day "loading" cycle and a night "unloading" cycle. The absorbent and refrigerant pair will be anhydrous calcium chloride and ammonia. The collector and generator will be of a flat plate configuration. The flat plate generator shall be large enough to harness enough heat to drive approximately 0.34kg of ammonia from the calcium chloride. The condenser shall be a water jacketing condenser and should have enough water to condense 0.34kg of ammonia. The evaporator pipe shall have a volume large enough to contain 0.34kg of liquid ammonia. The evaporator box shall be large enough to produce 0.91kg of ice. The entire system shall be made of schedule 80 black steel pipe and all fitting shall be rated at 3000psi. All gauges and valves shall be either steel or stainless steel. A 350psi relief valve shall be installed in case of emergency.

2.2. Input Data

The input data from this data were gotten from Codes, Standards, Textbooks and other trusted sources. They input data can be categorized into data pertinent to this case study and constants.

The input data pertinent to this case study include; Mass of Ammonia $m_{ammonia}$ (kg) = 0.35; Mass of evaporator m_{evap} (kg) = 4.04; Irradiance of solar PV panels I_{pv} (W/m^2) = 800; Area of one solar PV panel A_{pv} (m^2) = 1.24 (taken from Sun Power website).

Constants used in calculating the size of the design components include; Specific Heat Capacity of Water $C_{p,water}$ (kJ/kgK) = 4.187; Specific Heat Capacity of Ice (kJ/kgK) = 2.108; Latent Heat of Fusion of Water $h_{water \rightarrow ice}$ (kJ/kg) = 334; Latent Heat of Condensation of Ammonia $h_{c,ammonia}$ (kJ/kg) = 1371; Density of ammonia $\rho_{ammonia}$ (kg/m^3) = 682; Density of water ρ_{water} (kg/m^3) = 1000; Constant of Reaction Calcium Chloride and Ammonia $R_{CaCl2-NH3}$ (kJ/kg) = 2300; Latent Heat of Vapourization of Ammonia $h_{v,ammonia}$ (kJ/kg) = 1371; Specific Heat Capacity of Steel $C_{p,steel}$ (J/kgK) = 502; Ammonia Gas Constant $R_{ammonia}$ (kJ/kgK) = 0.488.

2.3. Design Assumptions for Prototype

a. Coefficient of performance of refrigeration, COP_R (-), is assumed to be 0.75.
b. The solar PV operates a 5 Hour Cycle.
c. The solar PV panel efficiency, $\eta_{pv,panel}$ = 0.15
d. The degradation factor of the solar PV panel, $\eta_{pv,deg}$ = 0.76 (dust, etc.)
e. The solar PV panel electrical conversion, $\eta_{pv,conversion}$ = 0.77
f. The Design Safety Factor, S.F. = 1.25
g. T_a (K) = 25; T_i (K) = -5; T_o (K) = 0
h. Ammonia is at condensation point (doesn't require cooling prior to condensation).
i. The evaporator must be able to hold 0.34kg of ammonia which has been driven off from the generator.
j. Time during which the reaction of $CaCl_2$ and Ammonia occurs is 14400 seconds (4 Hours).
k. Initial temperature of water to be converted to ice, $T_{i,water}$ (K) = 294.261
l. Target/Final water/ice temperature, $T_{f,water}$ (K)= 268.15
m. The assumptions made to calculate the maximum

pressure the system could experience are:

i Zero pounds of ammonia is condensed;

ii System volume is V (m^3) = 0.006;

iii System temperature is T (K) = 355.

2.4. Procedure and Algorithms

a) To calculate the amount of solar PV panels needed to make 100 lbs of ice

i Power needed to make 100 lbs of ice in five (5) hours;

$$Power = \frac{m_{water} \times (C_{p,water} (T_a - T_O) + h_{water \to ice} + C_{p,ice} \times (T_O - T_i))}{(5\ hrs \times 3600s)} \quad (1)$$

ii Energy required to make 100 lbs of ice in five (5) hours (W_{net})

$$W_{net} = \frac{Power}{COP_R} \quad (2)$$

iii The available solar energy (E_a)

$$E_a = I \times 5hrs \times \eta_{pv,panel} \times \eta_{pv,deg} \times \eta_{pv,conversion} \quad (3)$$

iv Panel coverage area ($Area_{coverage}$)

$$Area_{coverage} = \frac{W_{net}}{E_a} \quad (4)$$

v Number of solar PV panels needed to make 100 lbs of ice in 5 hours (N_{panels})

$$N_{panels} = \frac{Area_{coverage}}{A_{pv}} \quad (5)$$

b) For the condenser sizing calculations, the following procedural algorithms were followed;

vi Heat removed from ammonia during condensation (Q_a)

$$Q_a = (m_{ammonia}) \times (h_{c,ammonia}) \quad (6)$$

vii Heat absorbed by water during ammonia condensation (Q_w)

$$Q_w = Q_a \quad (7)$$

viii Mass of water needed to achieve condensation ($m_{water,condenser}$)

$$m_{water,condenser} = \frac{Q_w}{C_{p,water} \times \Delta T} \quad (8)$$

ix Required volume of the condenser ($V_{condenser}$)

$$V_{condenser} = \frac{m_{water,condenser}}{\rho_{water}} \quad (9)$$

c) For the evaporator sizing calculations, the following procedural algorithms were adhered to;

x The required volume of the evaporator pipe ($V_{evaporator}$);

$$V_{evaporator} = \frac{m_{ammonia}}{\rho_{ammonia}} \quad (10)$$

xi The length of the evaporator pipe (L_{evap}), assuming a pipe of radius (r) has been selected;

$$L_{evap} = \frac{V_{evaporator}}{\pi r^2} \quad (11)$$

d) For the chemical reaction calculations, the following equations were used;

xii Energy required to separate NH_3 from $CaCl_2$ ($E_{CaCl2\text{-}NH3}$)

$$E_{CaCl2-NH3} = (m_{ammonia}) \times (R_{CaCl2-NH3}) \quad (12)$$

xiii Power required to perform the separation in four (4) hours ($P_{CaCl2\text{-}NH3}$)

$$P_{CaCl2-NH3} = \frac{E_{CaCl2-NH3}}{4\ hrs \times 3600s} \quad (13)$$

e) To calculate the maximum amount of ice that can be produced using 0.34kg of ammonia;

xiv Heat absorbed by ammonia during evaporation ($Q_{a,evap}$);

$$Q_{a,evap} = h_{v,ammonia} \times (m_{ammonia}) \quad (14)$$

xv Heat absorbed by steel evaporator pipe (Q_{steel});

$$Q_{steel} = m_{evap} \times (C_{p,steel}) \times (T_{i,water} - T_{f,water}) \quad (15)$$

xvi Heat absorbed by water during fusion into ice (Q_{freeze});

$$Q_{freeze} = Q_{a,evap} - Q_{steel} \quad (16)$$

xvii Maximum amount of ice to be produced (m_{ice});

$$m_{ice} = \frac{Q_{freeze}}{(C_{p,water} \times (T_{i,water} - T_{f,water})) + h_{water \to ice}} \quad (17)$$

f) To obtain the maximum operating pressure the system could experience (MOP);

$$MOP = \frac{m_{ammonia} \times R_{ammonia} \times T}{V} \quad (18)$$

g) To prove that target temperatures necessary to drive the reaction was possible;

An AUTOCAD 3D model was created of the flat plate collector to perform a finite element analysis (FEA). This analysis was done to determine if 186°F inside the pipe was high enough to drive the system taking into account the amount of heat energy the calcium chloride ammonia mixture would remove. According to calculations, the calcium chloride ammonia mixture absorbs approximately 250 BTU's of energy alone, so the entire generator section would have to absorb much more energy to drive this system due to all the inevitable heat losses. After the nodal mesh system was set up in the computer FEA simulation analysis, it was left to run at a time step of 30 seconds for one hour. For a factor of safety, a copper fin surface temperature of 175°F (353 K) was used in the computer simulation FEA analysis.

2.5. Parts Drawings

Parts and assembly drawings for the flat plate solar collector are shown in this section:

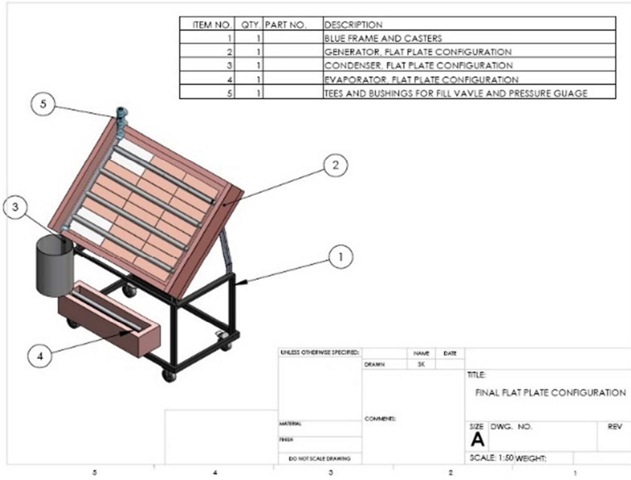

Figure 3. *Final flat plate configuration.*

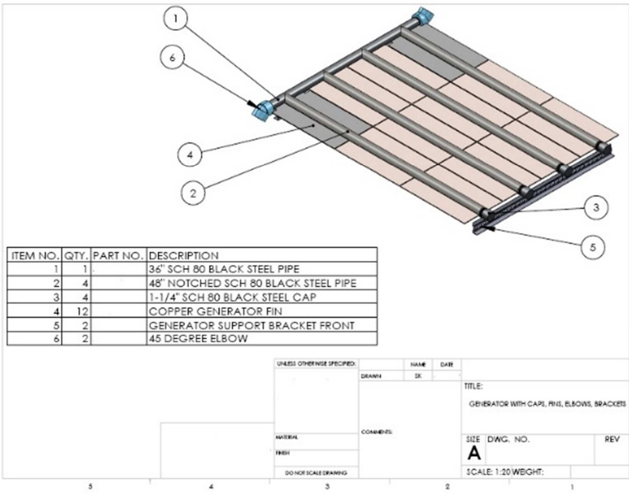

Figure 4. *Generator with caps, pins, elbows, brackets.*

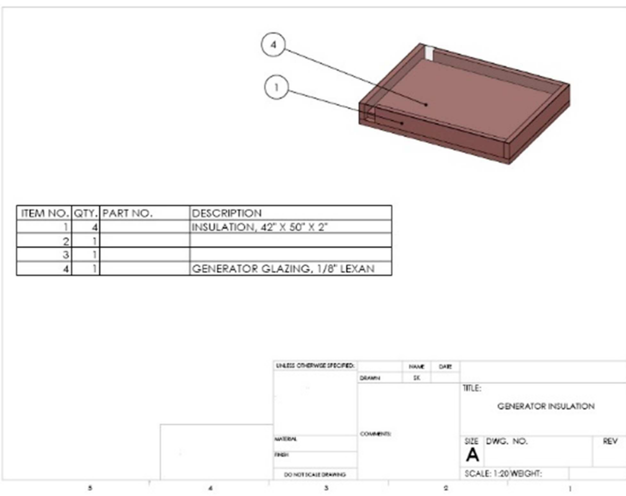

Figure 5. *Generator Insulation.*

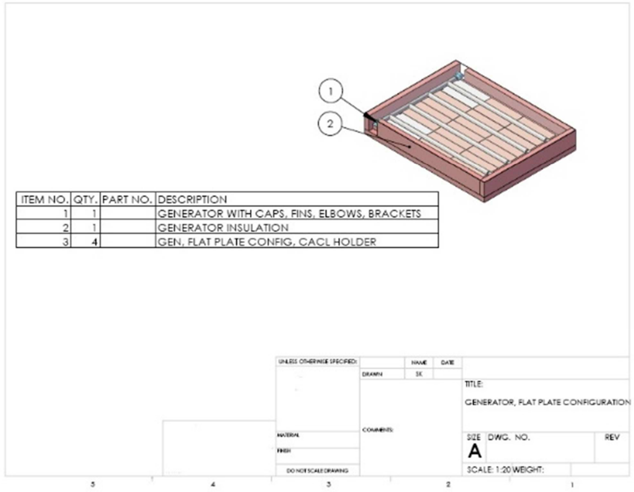

Figure 6. *Generator, Flat Plate Configuration.*

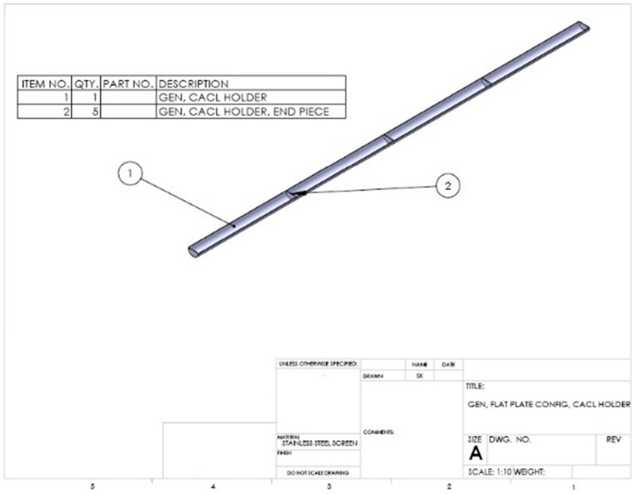

Figure 7. *Gen. Flat Plate Config, $CaCl_2$ Holder.*

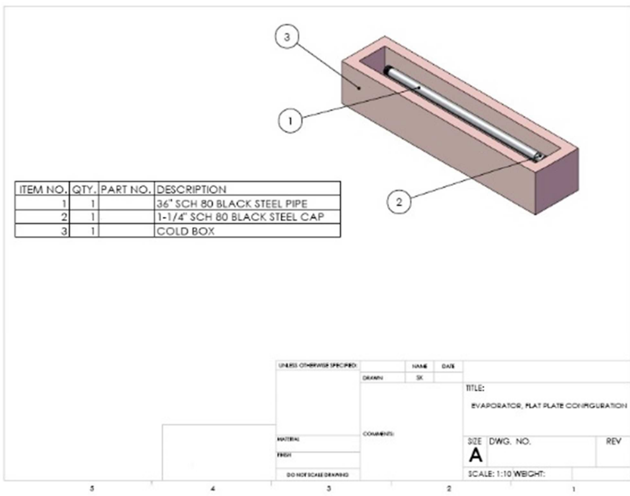

Figure 8. *Evaporator, Flat Plate Configuration.*

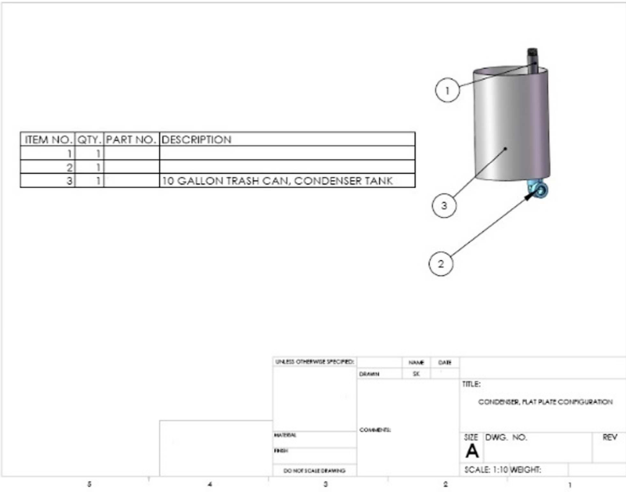

Figure 9. *Condenser, Flat Plate Configuration.*

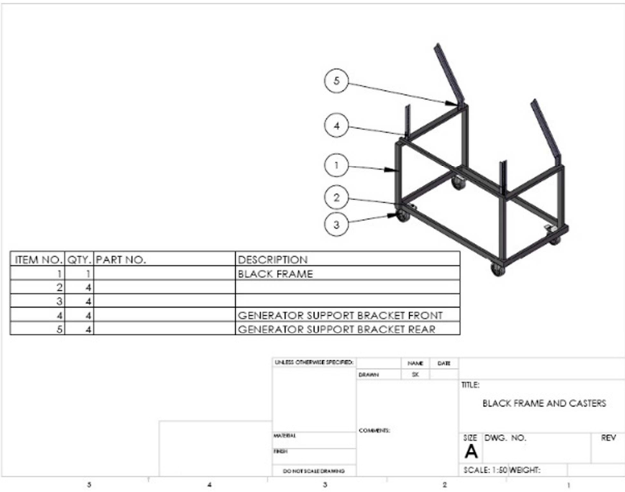

Figure 10. *Black Frame and Casters.*

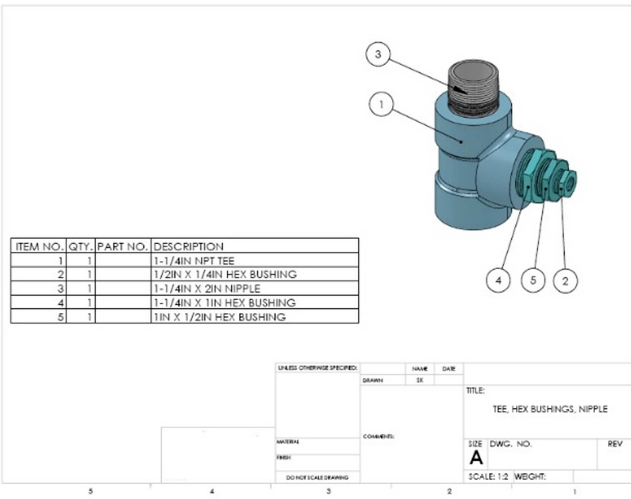

Figure 11. *Tee, Hex Bushings, Nipple.*

3. Results and Discussions

The primary objective of the study was to prove the concept of a flat plate solar collector or a solar driven intermittent vapor absorption system as a more efficient alternative to a solar PV powered refrigerator. The secondary objective was to achieve target generator and evaporator temperatures respectively. Raw input data (from section 2.2) were input into equation (1) to (18) to obtain the required system design parameters. An FEA was also performed to simulate the feasibility of the flat plate collector. The results are stated in this section.

3.1. Finite Element Analysis (FEA) Results

The FEA results revealed that with a copper surface temperature of 353K and energy removed by the calcium chloride ammonia mixture, the inside pipe surface temperature was 351K. See Figure 12 below showing the nodal mesh points as well as temperature gradient scale detailing the 351K measured inside the generator.

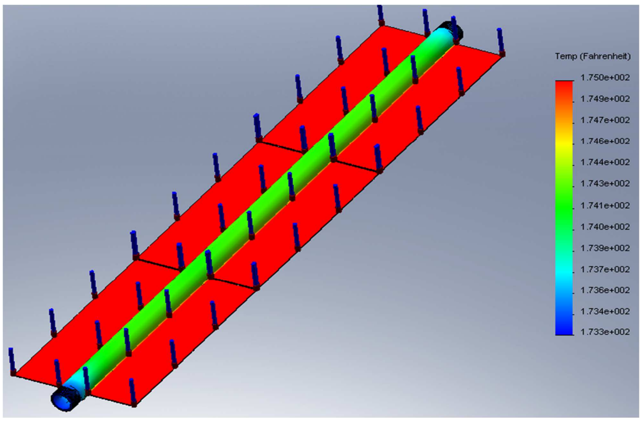

Figure 12. *Finite Element Analysis of Collector Pipe.*

3.2. Solar PV Alternative

The total power to create 100 lbs of ice was calculated to be 1.6 kW after taking into consideration the time and assumed COP of the cycle. After determining the power required, and then the available solar energy needs to be calculated. There are many programs that can provide the available irradiance; however, a quick calculation was better suited for this. The result was an irradiance of 351 W-hrs/m^2. After determining the coverage area of PV panels to be 22.8 m^2, the decision was made not to go with this alternative since the coverage area is rather large and is not feasible.

3.3. Absorbent and Refrigerant

The two chemical components of the device are Calcium Chloride ($CaCl_2$) and Ammonia (NH_3) needed to be balanced in order for the device to work properly. Complementary amounts of each chemical were needed in order for the reaction to occur and for the device to function properly. A chemical balance calculation showed that one mol of calcium chloride was needed for every 8 mol of ammonia. The assumption was made that approximately 25% of the ammonia present in the device would remain bonded to the calcium chloride. The amount of liquid ammonia needed to make 0.91 kg of ice was calculated to be 0.34 kg therefore the device would need to be initially charged with 0.454 kg ammonia. The molecular weights of the chemicals showed that 1.22 times the amount of ammonia was needed in calcium chloride making a 0.454 kg ammonia and 0.553 kg calcium chloride mixture.

3.4. Condenser Size

Water is the most readily available liquid for cooling so a calculation was performed in order to determine the volume of water needed in the condenser. The condenser would need to condense 0.34 kg of ammonia from vapor to liquid state. Taking into account the heat of condensation of ammonia and specific heat of water the mass of water needed was calculated to be approximately 28 kg. Therefore, the condenser should be able to hold 28 liters of water.

3.5. Evaporator Size

The evaporator will be a simple horizontal pipe, house in an insulated box. The evaporator must be large enough to accommodate the required amount of ammonia. Liquid ammonia occupies approximately one cubic meter for every 682 kg. The required mass of ammonia is 0.34 kg which means the volume of the evaporator needs to be approximately 0.0005 m3 or 0.5 liters. Based on this a 0.4-meter length of 40 mm nominal diameter black steel pipe was chosen.

3.6. Copper Fin-Steel Pipe Stress due to Thermal Expansion

In order to ensure that the brazed joint between the copper fin and steel generator pipe would not fail due to thermal loading the stress in the joint due to thermal expansion was calculated. The shear stress in the joint was determined to be 59.2 MPa well below the maximum allowable for the material of 250 MPa.

3.7. Maximum Operating Pressure

The device piping and fittings must be designed to withstand the maximum possible pressure of the system. This pressure was found by using the ideal gas law and assuming that no ammonia is condensed. Given this worst-case scenario it was determine that the system needed to be able to withstand 1400 psi.

3.8. Flat Plate Collector

Due to the reduced size of the spring device it was decided that a flat plate collector design would be used. The overall loss coefficient of the flat plate collector was calculated using a thermal network analysis that accounted for conduction, convective and radiation resistances. The system was assumed to be under steady state with constant irradiance. Form these calculations it was determined that a collector area of 0.93 square meters would be capable of producing the needed temperatures and heat transfer rate.

3.9. Performance Results

3.9.1. Generator Temperature Test

Once the generator section had been assembled, a temperature test was performed only on the generator to verify and confirm our initial experimental results from the small-scale mockup. From Figure 13 below, the generator temperature inside the pipe denoted by a dashed orange line reached temperatures between 80°C (176°F) after about an hour and maintained 90°C (194°F) for the duration of the loading day cycle. A high temperature of 97°C (207°F) was observed near 1:30pm. The high temperatures proved our initial assumptions and conjectures correct. In fact, the full-scale generator reached higher temperatures than those predicted by the Finite Element Analysis.

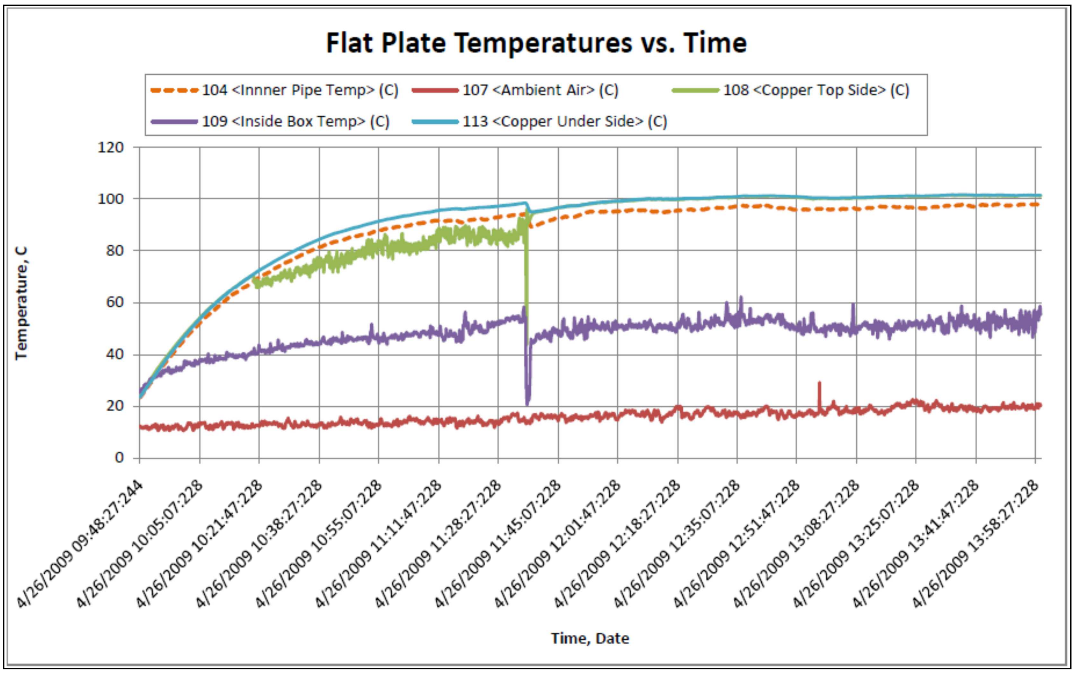

Figure 13. *Flat Plate Temperature test to determine generator temperatures over a 4-hour period.*

3.9.2. System Pressure Leak Test

After the prototype was completely finished, it was put through a rigorous pressure test for safety and to check any possible leaks. The apparatus was filled with helium, an inert gas, to near 300psig and left overnight. The pressure test revealed no pressure leaks anywhere. This confirms that no ammonia will escape during intermittent operation. Once the system was fully charged with one pound of ammonia, the actual performance tests began.

3.9.3. System Ammonia Charge

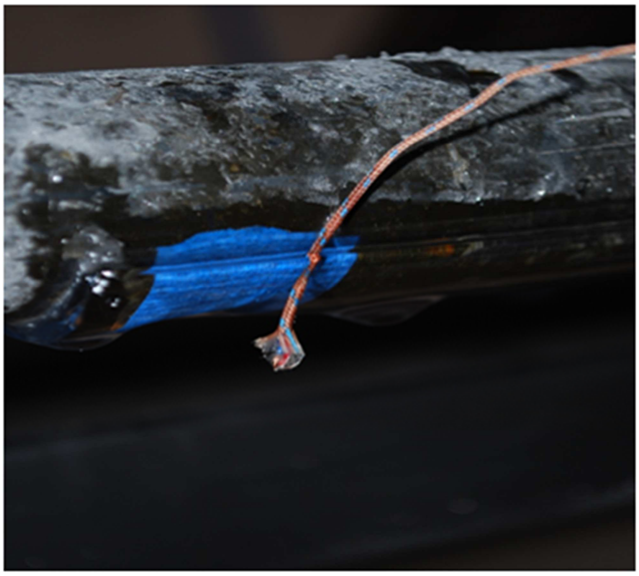

Figure 14. *A thermocouple is frozen in the layer of ice on the evaporator pipe.*

With the prototype completed, it was filled with calcium chloride and charged with ammonia. A vacuum was pulled on the device. A vacuum helps the ammonia fill the void in the system; otherwise, there will be entrapped air. The system was filled with about one and a half pounds of ammonia. Due to gravity, liquid ammonia filled into the lowest point in the system. This is also representative of a night time cycle producing ice. The team was very excited to see ice production (Figure 14).

3.9.4. System Final Performance Test

Figure 15 and Figure 16 shows the latest temperature results and irradiance readings for the loading day cycle. The loading tests were performed for almost eight hours. Initially, there was no visible sun, and thus, no temperature changes. At about 9:30am, the sunlight was visible and temperature as well as irradiance began registering. It took a little more than two hours for the generator copper fin top surface temperature denoted by the red colored line to begin leveling off over 100°C (212°F). The copper fin surface temperature was held constant over five hours at 105°C (221°F).

About 4:00pm, the irradiance changes erratically to almost 1,500 W/m^2. This was caused by the team members placing a foil reflector on the top edge of the generator to reflect more irradiance onto the generator before the device was to begin a simulated night cycle. This action also increased the copper fin surface temperature up to 109°C (228°F). A four-degree rise in temperature over 20 minutes was observed.

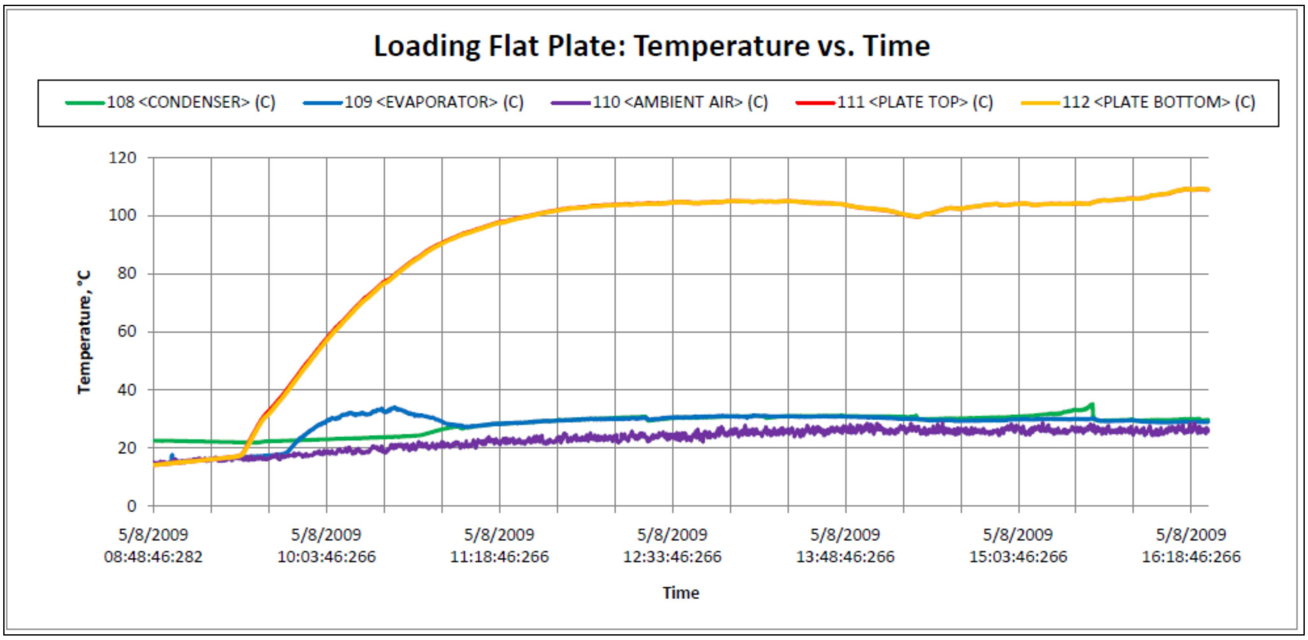

Figure 15. *Completed device Temperature performance test during loading day cycle.*

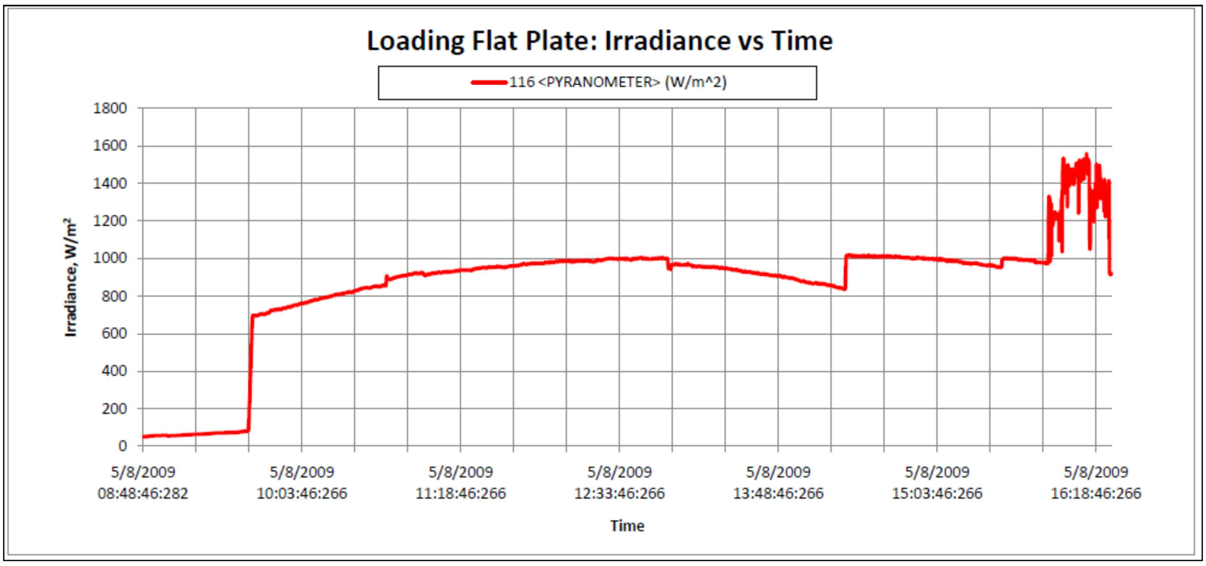

Figure 16. *Completed device Irradiance test during loading day cycle.*

In the simulated unloading night time cycle, the evaporator was enclosed in an insulated box. The results can be seen in Figure 17. As shown, the steep decrease in generator temperature from 109°C (228°F) down to 40°C (104°F) occurs in about 30 minutes. All the while, the evaporator temperature drops from 28°C (82°F) down to 0°C (32°F) during this time.

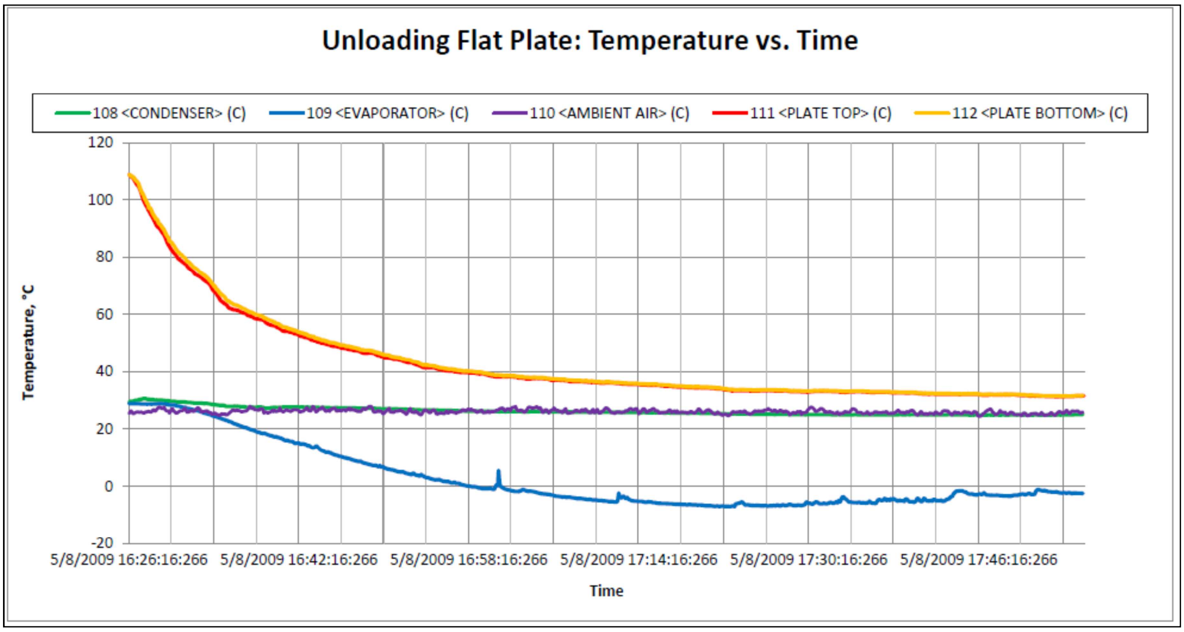

Figure 17. *Completed device performance temperature test during unloading night cycle.*

During most of the simulated night cycle, the evaporator pipe was kept inside the insulated box undisturbed. Condensation was observed on the evaporator pipe (Figure 18) 10 to 15 minutes after the night cycle began. No temperature measurement was taken inside the insulated box; however, the air temperature inside the box was much lower than ambient. At one point, when opening the insulated box to observe the evaporator pipe, a small draft of heavy cold dry air escaped through the opening at the bottom.

Figure 18. *Evaporator pipe with condensation enclosed inside an insulated box.*

The exciting aspect about this simulated night cycle is that the evaporator temperature drops below water's freezing point after 30 minutes. The lowest evaporator temperature reached was -7.1°C (19°F) after about 45 minutes. The evaporator surface temperature was cold enough to turn water into ice. Water was sprayed onto the evaporator pipe and as the water began to drip off the pipe it froze creating small icicles. See Figure 19 below.

Figure 19. *A glossy layer of ice surrounds the evaporator pipe with icicles forming underneath.*

This was the second time the test was run. For this second test, it was decided not to submerge the evaporator pipe in water since the result did not create ice but 55 °F (12.8°C) chilled water. Instead, water was sprayed onto the evaporator pipe via a spray bottle. The second test objective was to record evaporator temperature readings without any water. If evaporator temperature readings were below water's freeze point for extended period of time, then ice production is possible.

The testing and performance of the prototype was successful and yielded large amounts of data. Generator temperatures reached well above target temperatures and evaporator temperatures dropped below water's freeze point.

4. Conclusion and Recommendations

The primary objective for the study was to prove the concept of a flat plate collector for an intermittent absorption refrigeration system. The flat plate collector concept proved viable. Major progress was made in the design and analysis of a flat plate collector that resulted in evaporator temperatures capable of producing ice. The most important thing realized with this prototype is that the process is repeatable.

The prototype was fully tested twice, and each time the evaporator temperature decreased well below ambient signifying an accumulation of liquid ammonia. From the first test, the team concluded that too much water was placed in contact with the evaporator. This meant extra energy the ammonia must extract just to bring the water's temperature down to 32°F (0°C). However, the first test wasn't a total letdown. It proved the flat plate concept possible since the result was chilled water. This led to a second test, and to avoid any doubts, the team simply wanted to observe the evaporator temperature with no water addition. The results as depicted by Figure 18 shows condensation, which meant the evaporator surface temperature dropped well below the dew point temperature of the ambient air. Ice was eventually formed as shown by Figure 19.

The team's hard work and determination made for an icemaker with repeat testing capability. This will help others to understand the intermittent absorption cycle. There were no ammonia leaks as tested by ammonia PH strips. Needless to say, the prototype was a success

By the end of the project several possible improvements had been noted that could possibly make fabrication of the device faster and more cost effective. One of the first improvements that must be addressed is the condenser. The condenser leaked water onto the evaporator. A sound design of a condenser is key whether it be a water condenser or an air condenser.

The ability to digitally measure in-device temperature and pressure at the generator and the evaporator would be very beneficial for system monitoring. Installing ammonia proof digital gauges would greatly benefit the data acquisition process and would definitely yield more improved devices in the future.

One major downfall of using ammonia is that it dictates using steel or stainless-steel pipes. Flexible steel piping joints do exist but they are very expensive. If the device did have a flexible joint, multiple joints, it would greatly improve the ability to track the movement of the sun thus improving the efficiency of the device.

Developing a way to remove ice from the system would also greatly improve the overall design of the device. Currently the evaporator is housed within an insulating box where water trays could be placed for ice harvesting. A system that makes it more convenient to harvest ice or an insulating box capable of housing perishable goods could make the device directly applicable to day-to-day life.

References

[1] Coulomb, D., Dupon, J. L., & Pichard, A. (2015). The Role of Refrigeration in the Global Economy—29th Informatory Note on Refrigeration Technologies. *International Institute of Refrigeration, Paris, France*.

[2] Koronaki, I. P., Cowan, D., Maidment, G., Beerman, K., Schreurs, M., Kaar, K., and Cazauran, X. (2012). Refrigerant emissions and leakage prevention across Europe–Results from the RealSkillsEurope project. *Energy*, *45*(1), 71-80.

[3] Africa Energy Outlook (2014). A focus on energy prospects in Sub-Saharan Africa. World Energy Outlook Special Report, *International Energy Agency IEA*.

[4] Nkwetta, D. N., Smyth, M., Van Thong, V., Driesen, J., & Belmans, R. (2010). Electricity supply, irregularities, and the prospect for solar energy and energy sustainability in Sub-Saharan Africa. *Journal of renewable and sustainable energy*, *2*(2), 023102.

[5] Subin, R. (2011). Country: India's cold chain industry. *Indo-American Chamber of Commerce, available at https://www.iaccindia.com/userfiles/files/India's%20Cold, 20*.

[6] International Institute of Refrigeration (IIR), (2009). The Role of Refrigeration in Worldwide Nutrition–5th Informatory Note on Refrigeration and Food.

[7] United Nations, World Economic and Social Survey 2013: Sustainable Development Challenges, United Nations publication. Retrieved April 14, 2019 from https://sustainabledevelopment.un.org/content/documents/2843WESS2013.pdf.

[8] Pearson, A. (2008). Refrigeration with ammonia. *International journal of refrigeration*, *31*(4), 5.

[9] Vanek, S., Vanek, J., Green, M. (1996). A Solar Ammonia Adsorption Icemaker. Homepower Magazine: Issue #53.

[10] Bhatkar, V. W., Kriplani, V. M., & Awari, G. K. (2013). Alternative refrigerants in vapour compression refrigeration cycle for sustainable environment: a review of recent research. *International Journal of Environmental Science and Technology*, *10*(4), 871-880.

[11] Zeyghami, M., Goswami, D. Y., & Stefanakos, E. (2015). A review of solar thermo-mechanical refrigeration and cooling methods. *Renewable and Sustainable Energy Reviews*, *51*, 1428-1445

[12] Cengel, Y. A., & Boles, M. A. (2015). *Thermodynamics: An Engineering Approach*. 8th Edition, McGraw-Hill, New York.

[13] Cota, A., & Foster, R. (2010). Photovoltaics for Rural Development in Latin America: A Quarter Century of Lessons Learned. *Solar Collectors and Panels, Theory and Applications*, 55-78.

[14] Goyal, P., Baredar, P., Mittal, A., & Siddiqui, A. R. (2016). Adsorption refrigeration technology–An overview of theory and its solar energy applications. *Renewable and Sustainable Energy Reviews*, *53*, 1389-1410.

[15] Wang, D. C., Li, Y. H., Li, D., Xia, Y. Z., & Zhang, J. P. (2010). A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems. *Renewable and sustainable energy reviews*, *14*(1), 344-353.

[16] Guerrero, L., and Pascua, Y. (2008). Solar Ice Maker: A solar energy adsorption-refrigeration system. San Jose State University.

[17] Farshi, L. G., Ferreira, C. I., Mahmoudi, S. S., & Rosen, M. A. (2014). First and second law analysis of ammonia/salt absorption refrigeration systems. *International journal of refrigeration*, *40*, 111-121.