Design of a Cooling System Using Geothermal Energy for Storage of Agricultural Products With Emphasis on Irish Potatoes in Rwanda, Africa

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ABSTRACT

This study focuses on the design of a cooling system for storage of agricultural products. An absorption refrigeration unit which uses a geothermal heat source to drive the absorption cycle in a chilling process, in a 25°C environment with a compartment temperature of 5°C. This system is to provide the cooling to the cold storage with a heat load of 140 kWt. The parameters mainly monitored are COP, heat transfer rates, mass flow of a geothermal fluid and the power required to run the cycle. Thermodynamic analysis of the cycle concluded that the COP of the absorption refrigeration cycle is 0.49, but can go as high as 0.6 when a heat exchanger is used.

1. Introduction

The development of geothermal energy resources in Rwanda is at early stages compared to some other East African countries such as Kenya and Ethiopia. The exploration of this resource really boomed in 2006 with a view of diversifying energy sources in the generation of electricity to meet the electricity demand in the country. The volcanoes area, the geological context and the hydrothermal manifestations of Rwanda are an indication of the existence of potential geothermal systems. Early geothermal investigations pointed out the north-west area as a potential for large, high temperature geothermal systems, while the rift in the south-west part of the country along the Lake Kivu is believed to present an environment for low to moderate temperature resources (Demange et al., 1983; Newell et al., 2006). The current strategy of the Government of Rwanda (GoR) is to determine how much geothermal potential is available for the country to meet its energy demand. This step will be implemented by drilling exploration wells to prove the existence of the resource.

Geothermal energy is a sustainable form of energy that can be used directly as heat or indirectly by conversion to other forms of energy. Geothermal resources in the range of 80-150°C can preferably be used to power the heat driven processes, such as cooling systems, and in absorption refrigeration system which uses thermal energy as the heat source. Resources within this temperature range are likely to be found in Rwanda's geothermal fields. Karisimbi, where exploration drilling activities began recently, is one of them. Rwanda is an East African country located along the Western Branch of the East African Rift system with a surface area of 26,338 km^2 and a population estimate of 12 million inhabitants (NISR, 2013). Agriculture is the main industry in Rwanda with about 90% of the population engaged in subsistence agriculture, with few natural resources. Irish potato is the most common crop produced on large scale in the Northern Province where most of Rwanda's geothermal fields are located. To provide long term storage of the potatoes, cold storage would be desirable. Absorption refrigeration cycle (ARC) uses the evaporation of a liquid refrigerant to absorb heat. The refrigerant goes through a cycle so that it can be re-used. The purpose of this study is to assess ARC refrigeration processes and model the system by analysing the thermodynamic properties of the working fluids and setting up the cooling unit. There are two well-known refrigeration systems which are vapour compression and vapour absorption cycles. Variation of the performance of ARC system will be observed, operating from a proposed geothermal heat source to power the cycle with a case study on the Karisimbi geothermal field.

2. Geothermal Resources in Rwanda

2.1. Geological and Structural Settings

Rwanda hosts two prospective areas: the National Volcanoes Park and the faults associated with the East African Rift near Lake Kivu. The National Volcanoes Park was identified as a potential host for large, high-temperature geothermal systems, while the rift provides an environment for small, low-to moderate-temperature resources. The current study involves the northwest part of Rwanda that includes the National Volcanoes Park. The main structural trends of this area are controlled by the old basement rocks. The Nyiragongo volcano to the west of the area has been erupting periodically, with the recent eruption in 2002 (Figure 1). This signifies that a heat source for a geothermal system could exist around the major volcanic chain. The area of exploration is between the Nyiragongo volcano to the west, the Muhabura volcano to the east and Gisenyi to the south. The major structural trends, show that the older rift border faults have a predominantly northwesterly trend while the younger eastern rift border faults have a northeasterly trend (BGR, 2009).Other important structures include an accommodation zone, which marks the boundary between the basement rocks and volcanic rocks. It is anticipated that this structural pattern is probably buried below the younger volcanic rocks (Onacha, 2008).

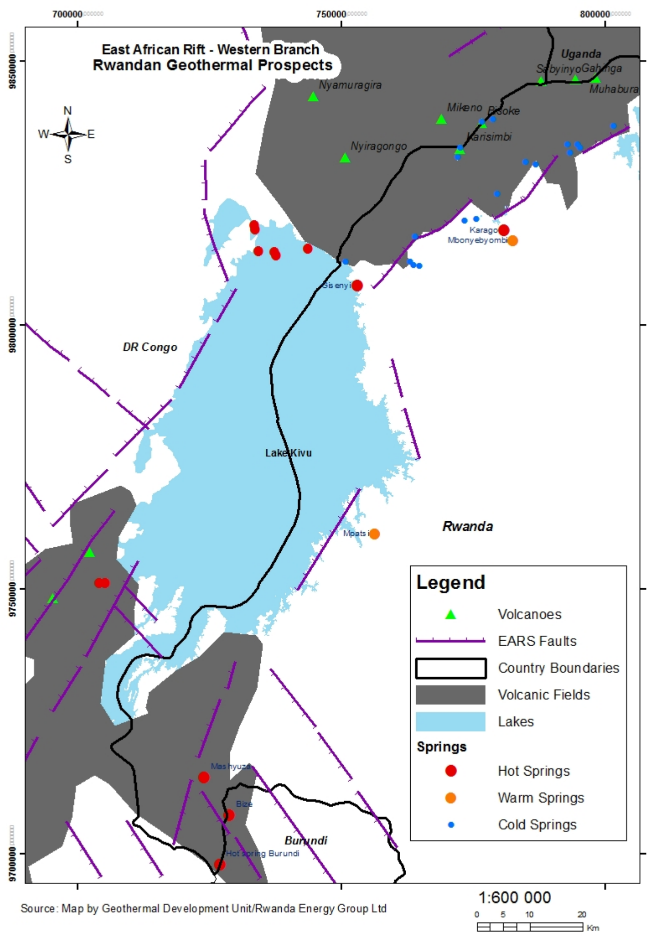

Figure 1. Location map of the geothermal fields in Rwanda.

2.2. Geothermal Fields

The geothermal areas in the western region cover an area of about 900 km^2 and it has been further subdivided into the three regions of Karisimbi, Gisenyi and Kinigi. The Karisimbi geothermal prospect is found on the southern slopes of the Karisimbi volcano.The Karisimbi field is part of the National Volcanoes Park. No geothermal manifestation such as fumarole or hydrothermal alteration have been reported in this area. However, a couple of hot springs are located south and out of the volcanic field, as shown in Table 1, with the highest temperature of 64°C at Karago (located in the southern part of the Karisimbi geothermal prospect).

2.3. Karisimbi Geothermal Field

The Karisimbi geothermal field is situated in the western province and occupies an area of about 200 km^2. The prospect lies to the south of the National Volcanoes Park (NVP). Northern and Western Provinces of Rwanda have fertile soils around NVP with a heavy downpour and an annual rainfall with an average of 800 mm which are favourable for Irish potato growing. The proposed sites for exploration drilling are found to the north of Mukamira. The calculated temperature ranges from the geothermometers are low (Table 1), probably due to the nephelinites absorbing silicate hot springs which produce sodium bicarbonate water with temperature between 70- 75°C. The flow rates from all the vents are estimated to be 2-5 kg/s and are controlled by fractures. It is postulated that some of the vents could be buried below the lake's surface. Based on geochemical geothermometers, the reservoir temperature is estimated to be between 150 and 210°C (Newell et al., 2006; BGR, 2009).

Table 1. Measured and calculated temperatures with geochemical geothermometer.

Location	Surface Temp (°C)	Quartz (°C)	Na/K (°C)
Karago	64	126	147
Gisenyi	70-72	107	175

3. Geothermal Utilization and Direct Use Opportunities

The Government of Rwanda also intends to develop direct utilization of geothermal resources in the agricultural sector using greenhouses, and drying rice and fish. Other direct uses will include the uses of geothermal heat in pyrethrum processing and for drying tea and coffee.

3.1. Case Study on Irish Potatoes

3.1.1. Irish Potatoes Value Chain in Rwanda

The potato has become an important crop in Rwanda with about 133,000 hectares under cultivation; more than 1 million metric tonnes (MT) of potatoes are produced annually (Agri, 2012). The Irish potato requires a relatively cool and moist climate to achieve high production. Musanze, Burera, Gicumbi and Nyabihu districts account for 90% of the national potato production in Rwanda. A significant portion of the Irish potatoes produced are consumed in the areas of production and there is no potato storage or processing plant in Rwanda yet. Most potatoes are transported to the markets immediately after harvest, generally unwashed in large bags. In most cases, the farmer does not know the price he will receive for his potatoes before reaching the main market; this becomes a challenge for them in terms of marketing and economic planning.

Table 2. Potatoes production cost and selling price in Rwanda.

Potato	Size & units	Amount (USD)
Production Cost	/ha	1,068-2,595
Selling price	/kg	0.099-0.46
Average production cost	/kg	0.13
Average yield cost	9,400 kg/ha	1,277

3.1.2. Potato Growing Seasons

There are basically two seasons (A & B) for potato growing in Rwanda as shown in Figure 2, where the first season (A) starts from September to December and the second season (B) starts from February to May. Pl stands for planting, growing and H for harvesting time respectively.

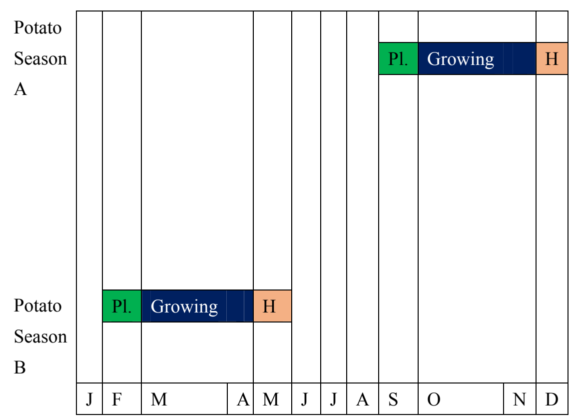

Figure 2. Potato growing seasons in Rwanda.

4. Statement of the Problem and Need for The Study

The potato production cycle in Rwanda is quite short with 3-4 months and follows two main growing seasons (Figure 2). In some regions however, it is possible to extend the growing cycle beyond those seasons if sufficient moisture is available in the soil. The lack of storage and processing facilities makes it necessary for Rwanda potato farmers to sell their production almost as soon as it is harvested; this is the current weakness of the Rwanda potato sector. The big challenge being lack of storage facilities for their production on large scale and leads to the immediate selling most of them to neighbour countries like Burundi and others at low prices, yet if they were some storage facilities, potatoes can be stored for some time and sold at competitive prices.

5. Potatoes Storage Conditions

5.1. Mid and Long-Term Storage

The objective of long-term storage is to maintain a consistent, ideal environment for the duration of the storage period. Long-term storage demands more critical control than short-term storage. Recommended storage temperatures depend upon crop condition, variety and intended end use. General recommendations for storage temperatures, relative humidity and duration are listed in Table 3.

Table 3. Potential storage duration of potatoes.

Potatoes	Temp (°C)	RH (%)	Potential Storage Duration
Fresh market	4-7	95-98	10 months
Processing	8-12	95-98	10 months
Seeds	0-2	95-98	10 months

5.1.1. Storage Capacity and Location.

It is desired to design a cooling system for storage of agricultural products with emphasis on potatoes. This storage facility is proposed to be built in the northern province of the country in Musanze district near the geothermal fields in Rwanda, in order to utilize geothermal heat. It has capacity of storing 312 tonnes of potatoes using wooden storage bins

(Figure 3). The others detailed dimensions and conditions are summarized in the tables below and the related refrigeration load calculations.

5.2. Refrigerated Cold Storage

5.2.1. Description of Storage Construction Materials and Insulation

Figure 3 shows the proposed arrangement of storage bins in cold store. Many different conditions must be considered while planning construction of cold warehousing facilities and requires an enormous degree of precision and attention to details. One of the most important things to consider is which concrete floor to use. Not all concrete floors are created equal and using the wrong one can lead to trouble and unnecessary expenses. Therefore, it is very important to get the best possible concrete floor system to meet your cold storage warehousing needs. There are many different methods that can be used to install them. This particular storage considered a concrete floor with a given water-cement ratio because the concrete strength is likely to be obtained in a given local depends primarily on the aggregate sources available. The maximum particle size and the quality of coarse aggregate will have a pronounced effect on concrete strength as will the gradation of the blended coarse and fine aggregate. This chilled room considered also the sealing system which best fits the needs of the cold storage and corresponding concrete walls and roof. Assuming homogeneous insulation and enough space were left above the storage bins purposely for lights and other cooling system ducts. Table 4 shows the details of the cold room.

The insulation materials used are wooden fiber which are residue and waste wood to produce a suitable low density wood fibre board which are easy, safe to work with and cost-effective. It is designed to be used inside the building as it offers additional insulation when used in interior walls, floors and ceilings. Wood fibre insulation can absorb moisture and has high vapor diffusion capability allowing the panels to act as a breathable structure. This helps to improve the indoor air quality by absorbing and releasing heat back later when the temperature decreases (see Table 5 for working and storage conditions).

Figure 3. 1000 kg proposed potato storage bins (Palletlink, 2013).

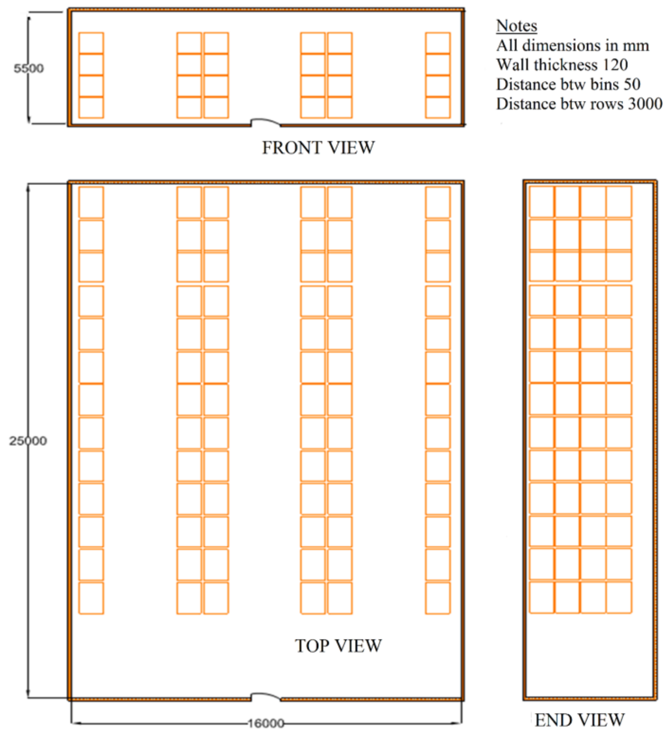

Figure 4. Overview of the bins in the chilled room.

Table 4. Details of the Cold Room.

Potatoes Storage		
Potatoes	***Units***	***Quantity***
Storage capacity	*bins*	*312*
Store dimensions	*m*	*L=25, W=16,H=5.5*
Volume (Vs)	*m^3*	*2,200*
Surface area including the floor(A)	*m^2*	*1,294*
Temperature difference (ΔT)	*°C*	*20*
Specific heat of Potatoes	*kJ/kg °C*	*0.82*
Rate of respiration	*W/kg*	*0.028*
Overall coefficient of Transmission	*W/ m^2 /°C*	*1.6*

Table 5. Working conditions and assumptions for the design system.

Conditions		
Loading weight & time	*104 bins (104,000kg of potatoes); 3 days to fill*	
Cooling rate	*1st day , 20 to 10 °C; 2nd day,10 to 5 °C*	
Air changes from door opening during cooling	*times per day*	*6*
Air changes from door opening during storage °C	*times per day*	*1.8*
Heat load to lower air from 20 (90% RH) to 10 (95% RH)	*kW/m3*	*0.45*
Heat load to lower air from 10 to 5 °C(95 % RH)	*kW/m3*	*0.087*
Assuming uniform insulation on the walls, ceiling and floor.		

5.2.2. Wooden Storage Bins

The storage bins under this design are made of cypress timber. The major advantages of wooden bins are low cost, superior strength, and having been the industry standard for long time. Wooden bin kits are produced and assembled locally which minimizes transportation cost from manufacturer to end users. Their dimensions are summarized in Table 6.

Table 6. Wooden bin in detail.

Wooden Storage Bins	Units	Value
Number of Bins	Pcs	312
Bin dimensions	m	L=1.5 ,W=1,H =1
Bin Weight	kg	90
Total weight of bins	kg	28,080
Storage capacity of the bin	kg	1000
Specific heat of the bin	kJ/kg °C	0.5

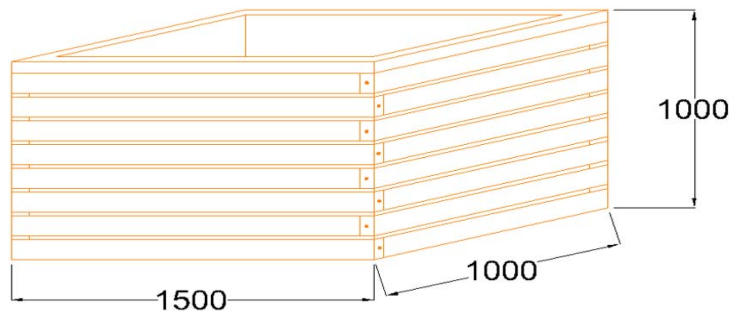

Figure 5. Storage bin.

5.2.3. Storage Heat Load Calculations

The total heat load consists of the amount of heat to be removed from the refrigerated room during a certain period. It is dependent on two main factors: heat leakage or heat transfer load and heat usage or service load, respectively. Thus, the following heat loads were considered in the design of this cold room; building transmission load includes; air change heat load, product heat load, heat usage load and miscellaneous heat loads.

5.2.4. Heat Load Calculation Scenarios

Heat load calculations are divided into two cases where one considers peak refrigeration load especially in filling up and empting the store, while the second one considers heat load when the room has attained the room storage temperature.

The storage facility took 3 days to fill and the temperature reduces in the following order to reach the storage room temperature; 20-10-5˚C.The total refrigeration for completely chilled storage room is 34 kWh.

Scenario A (Peak refrigeration) operates at 140 kWh while Scenario B is 34 kWh which is the heat load after the room has maintained constant temperature. The formulas used in heat load calculations are shown in the appendix.

Scenario A (Peak Refrigeration)

Table 7. Peak refrigeration load capacity.

Parameters	Values (kWh)
Building transmission load	*11.5*
Air change load from door openings	*10.2*
Product cooling	*71.2*
Miscellaneous heat loads	*4.4*
Heat of respiration during cooling potatoes	*24.5*
Maximum heat accumulated in storage before cooling completed	*4.9*
Total heat load during cooling	
Subtotal	*126.7*
Design margin 10%	*12.6*
Total required refrigeration	***140***

Scenario B (Storage Temperature)

Table 8. Storage temperature refrigeration load capacity (kWh).

Parameter	Value
Load during normal storage operation	
Building transmission load	*11.6*
Air change load from door openings:	*3*
Miscellaneous heat loads:	*4.4*
Respiration rate	*12*
Subtotal	31
Design margin 10%	*3.1*
Total required refrigeration	***34***

6. Theory of Refrigeration Systems

Refrigeration system is a process of removing heat from an object, mainly in a confined space, and rejecting the unwanted heat into a specific preferable environment; in other words, the refrigeration process is a method for lowering the temperature of an object. There are two common refrigeration systems which are widely used: vapor absorption refrigeration systems (ARS) and vapor compression refrigeration (CR) systems. This study mainly focus on the ARC system by evaluating its efficiency.

6.1. Vapor Absorption Cycles

Absorption refrigeration systems are much like in the vapor compression cycle but the compressor is replaced by a generator and an absorber. Refrigerant enters the evaporator in the form of a cool, low-pressure mixture of liquid and vapor at point (9) in Figure 6, Heat is transferred from the relatively warm water to the refrigerant, causing the liquid refrigerant to boil. The absorber draws in the refrigerant vapor at point (10) to mix with the absorbent. The pump pushes the mixture of refrigerant and absorbent up to the high pressure side of the system. The generator delivers the refrigerant vapor at point (7) to the rest of the system, the refrigerant vapor at point (7) leaving the generator enters the condenser, where heat is transferred to water at lower temperature causing the refrigerant vapor to condense into a liquid. This liquid refrigerant at point (8) then flows to the expansion device, which creates a pressure drop that reduces the pressure of the refrigerant to that of the evaporator. The resulting mixture of liquid and vapor refrigerant at point (9) travels to the evaporator to repeat the cycle.

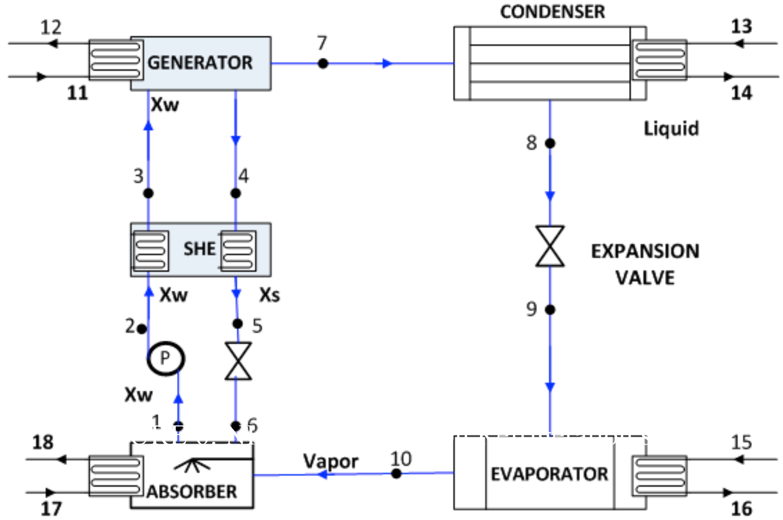

Figure 6. NH_3-H_20 absorbtion refrigeration system.

6.2. System Efficiency and Coefficient of Performance

Efficiencies of absorption chillers are described in terms of coefficient of performance (COP), which is defined as the refrigeration effect, divided by the net heat input. Single-effect absorption chillers have COPs of approximately 0.6-0.8 out of an ideal 1.0.Since the COP is less than one, the single-effect chillers are normally used in applications that recover waste heat such as waste steam from power plants or boilers. Double-effect absorption chillers have COPs of approximately 1.0 out of an ideal 2.0.While not yet commercially available, prototype triple effect absorption chillers have calculated COPs from 1.4 to 1.6. (Advanced design guideline series, 1998).Compared with mechanical chillers, absorption systems have a low coefficient of performance (COP = chiller load/heat input). However, absorption chillers can substantially reduce operating costs because they are powered by low-grade waste heat. The COP of absorption chiller is NOT sensitive to load variations and does not reduce significantly at part loads. It is recommended to use a solution heat exchanger in absorption systems; since it allows the solution from the absorber to be preheated before entering the generator by using the heat from the hot solution leaving the generator. Therefore, the COP is improved as the heat input at the generator is reduced. Moreover, the size of the absorber can be reduced as less heat is rejected. Experimental studies show that COP can be increased up to 0.6.when a solution heat exchanger is used.

6.3. Working Media

There are several refrigerant compounds that are used in refrigeration systems, but the most common are NH_3-H_20 and LiBr/H_20. LiBr/H_20 is mainly used in cooling/air conditioning applications where the temperature goes as low as 0 ˚C, LiBr/H_20 is then used as the absorbent and water as the refrigerant. (Ratlamwala et al., 2012). However, this study will consider NH_3-H_20 as the working fluid for the cycle. In the NH_3-H_20 solution, NH_3 is the refrigerant in the mixture. It has a low freezing point, high latent heat of vaporization and low cost. (Srikhirin et al., 2001).

6.4. ARS System Description and Mathematical Modeling

Geothermal fluids for heating of NH_3-H_20 mixture have technical specifications as shown in Table 9**;** geothermal hot water at 150°C for producing heat to run vapor absorption refrigeration cycle. The system includes a generator, absorber, condenser, evaporator and solution heat exchanger. The determination of the thermodynamic properties of each state point in the cycle, the amount of heat transfer in each component, and the flow rates at different lines depend upon the generator temperature , evaporator temperature, condenser temperature, absorber temperature, liquid-liquid heat exchanger effectiveness and refrigeration load. An absorption refrigeration system complete with solution heat exchanger is going to be modeled for water-ammonia system. In this refrigeration system, the absorption machine is to provide a cooling effect to the cold

Table 9. Initial design parameters for single effect ARC.

T_{source}	150°C
$\dot{m}_{source}$	3.8 kg/s
Q_{ref}	140 kWt
η_{pump}	0.95
η_{she}	0.60
T_{pinch}	5°C
$T_{Evaporator}$	5°C
$T_{condenser}$	38.9°C
$T_{Absorber}$	25°C
$pressure_{high}$	15bar
$pressure_{Low}$	2bar
$T_{reinjection}$	114.4°C
$T_{-cond\ inlet}$	25°C
$T_{-cond\ outlet}$	33.9°C

storage room with refrigeration load of 140kW$_t$ refrigeration/evaporator capacity. The effect of solution concentration to refrigeration performance is obtained by monitoring the strong and weak concentration differences in a certain range. It was assumed that the generator produced ammonia refrigerant with an ammonia concentration of 99.9 %. A complete list of initial design parameters are described in Table 9. Other parameters were freely determined to achieve a preferable machine performance.

7. Simulation Results and Discussion

In this simulation process, absorption refrigeration cycle were analyzed, thermodynamic properties at the various state points , energy flow rate at various components of the cycle, coefficient of performance and mass flow rates of the system by using input parameters being calculated through the EES model. Latent heat of refrigerants and the heat requirement to increase the solution temperature are the main key factors that affect the performance of a refrigerant. It was revealed that the absorption refrigeration system should be properly designed to achieve its maximum performance since different amount of heat source and cooling load affects refrigeration parameters. It is also very important to mention that the higher the temperature of the heat source, the better the COP. Also, the efficiency of an absorption machine quickly deteriorates as soon as the temperature of the heat source drops below the design figure. The refrigeration system for cooling Irish potatoes and thermodynamic analysis for proposed system was carried out and demonstrated that 150°C geothermal water with 3.8 kg/s flow rate was enough to provide cooling effect for the cold storage room with a refrigeration load of 140 kWt and also have the ability to provide more cooling effect for the expansion of the storage once a bigger storage facility is required. Tables A and B in the appendix, are for thermodynamic properties of state points for absorption refrigeration cycle and energy flows at the various component in the system respectively.

Conclusions

A cooling system for agricultural product using geothermal hot water as a heat source was designed for expected application in Rwanda, East Africa. The first law of thermodynamics was applied to a single stage ammonia-water (NH_3-H_20) vapour absorption refrigeration system, and the performance analysis of each component was carried out through mathematical model on EES. The results are summarized as:

1. Coefficient of performance of the system decreases with increasing inlet water temperature to generator (T11) keeping the outlet water temperature to generator (T12) constant.
2. A required refrigeration load of 140 kWh was achieved with a heat source of 150 ^{o}C geothermal water at a flowrate of 3.8 kg/s.
3. As the generator temperature increases, the COP of the system decreases.
4. The vapor formed in the generator contains not only ammonia, but also, to certain extent, water vapor, installing a water separator (rectifier) after the generator, decreases the water contents in the refrigerant and increases the system efficiency.

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APPENDICES

Formulas Used in Heat Load Calculations

Building transmission load: *Building transmission Load = A * U ** ΔT

Where *A is the outer surface area of the building,* m^2
U is overall coefficient of transmission, $W/m^2\ °C$
ΔT *is temperature difference, °C*

Air change heat load: $ACL = V_s * \rho(h_0 - h_i) * ACD$

Where *ACL is air change load due to door opening, infiltration, ventilation, etc., kWh*
V_s *is volume of the cold room,* m^3
h is enthalpy of air, kJ/kg
ρ *is density of air,* kg/m^3
ACD is the air change per day, number of times
(Subscripts o and i denote out and in respectively)

Miscellaneous heat loads: *Heat load dissipated by:*

*Lights = W * KJ/W * T*
*Fans = HP * kJ/HP * T*
*Labor = people * kJ/h * T*

Where W is Watts
HP is Horse power
kJ for kilojour

Product heat load: $PHL = W * c_p * \Delta T/t$

Where *PHL is the product heat load, kW*
W is potatoes weight, kg
c_p *is the specific heat of potatoes, (kJ/kg ˚C)*

Table A. Thermodynamic properties of state points for absorption refrigeration cycle.

State points	Specific Enthalpy [kJ/kg]	Mass flow rate [kg/s]	Pressure [kPa]	Specific entropy [kJ/k/kg]	Temp-erature [°C]	Concen-tration
1	-64.89	0.6356	2	0.4013	35	0.3678
2	-62.74	0.6356	15	0.4013	35.08	0.3678
3	301.9	0.6356	15	1.452	109.4	0.3678
4	491.2	0.5057	15	1.822	145	0.2056
5	32.84	0.5057	15	0.5627	40.08	0.2056
6	32.84	0.5057	2	0.5673	40.35	0.2056
7	1842	0.1299	15	5.523	145	0.999
8	183.6	0.1299	15	0.6396	38.87	0.999
9	183.6	0.1299	2	0.7464	-18.67	0.999
10	1261	0.1299	2	4.959	2.516	0.999

Table B. Energy flows at the various component in the system.

S. No	Description	Notation	Calculated Value (kWh)
1	Heat load in Generator	Qg	295.9
2	Heat load in Condenser	Qc	215.5
3	Heat load in Absorber	Qa	221.7
4	Heat load in Evaporator	Qe	140
5	Coefficient of Performance	COP	0.4914 (Dimensionless)