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Performance Evaluation of a Refrigeration System for Fresh Maize Storage

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Authors' contributions

This work was carried out in collaboration among all authors. Author OOC designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author NGO managed the write up of the study and the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: In this research project, a refrigeration system that will preserve the quality of fresh maize was developed.
Study Design: Design of refrigeration system.
Place and Duration of Study: Department of Industrial and Production Engineering, Federal University of Technology, Akure, Ondo State, Nigeria, between August 2017 and February 2018.
Methodology: The designed system consists of a cooling cabinet, compressor, condenser and an evaporator. The cabinet was designed to store up to 15 kg of maize and a compressor of 1/6 hp was used. The equivalent condenser and evaporator were selected with an equivalent expansion valve. R134a was used as the refrigerant. The cabinet walls were fabricated from mild steel (outside wall), stainless steel (inner wall) and glass wool (insulator).
Results: The fabricated system stores fresh maize above its freezing temperature of -1ºC. The system operating temperature ranges from -4 to 2.5ºC with a relative humidity of 90 to 95% for eight hours.
Conclusion: The fresh maize was stored for ten days without noticeable changes in the physical appearance and taste of the maize.

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Keywords: Maize; refrigeration; storage; temperature; quality.

1. INTRODUCTION

Maize (*Zea mays* L.) known in some English-speaking countries as corn is the third most important cereal crop in Africa [1]. It occupies less land area than either wheat or rice but has a greater average yield per unit area of about 5.5 tonnes per hectare [2]. According to Baributsa, et al. [3] maize reaches physiological maturity between 130 and 160 days after planting, depending on the variety. At this stage, the crop has a moisture content of about 30 percent and can be harvested provided that adequate storage facilities are available.

Maize is a good source of starch (65-70%), protein (8-10%), fat (3-4%) and some of the important vitamins and minerals (Shobha, et al. 2011). IITA (2007) established maize as an important source of oils, vitamin B and minerals. According to Dasbak, et al. [4] maize kennel is also rich in vitamins and fats.

Storage requirements for maize have changed significantly from the days when the farmer only had to worry about storing food and some seed for the following planting season [5]. However, maize is now mainly hybrid maize which, because of its shorter and looser husks, should ideally be stored shelled in a closed store if dry. Preservation of quality during long term storage is a problem in many parts of the world [6,7].

Maize grown by subsistence farmers is a staple food for millions of people around the world, especially in Sub-Saharan Africa and Central America. Maize has been in the diet of Nigerian's for centuries. Fresh maize is a living organism and continues to respire after harvest. Its sweetness and quality can rapidly deteriorate after harvest if not maintained at low temperatures. The losses of maize amount to millions of tonnes per year which could be available with no additional inputs of land, seed, fertilizer, and water [8].

Fresh-cut fresh corn kernels are extremely perishable because their respiration rate is very high; several times that of intact ears [1]. Therefore, there is a need to find appropriate post-harvest handling methods to preserve fresh maize, as well as to retard the deterioration processes [9]. Isik and Unal [6] explained the importance of the knowledge of physical properties of maize as essential engineering data in the design of machines, storage structure and processes for it. Also, Sobukola and Onwuka [10] emphasized that the determination of physical properties as a function of moisture content is important to design equipment for handling, storing and processing of fresh maize. The optimum storage temperature of most fruits and vegetables is about 0.5 to 1ºC above their freezing point to maintain their freshness.

Grains have a shelf life just like any food product. Shelf life is primarily determined by moisture content and temperature. Akintunde and Obadina [11] revealed that the shelf life of agricultural produce is mostly affected by environmental factors such as temperature, relative humidity, respiration, water loss, air movement, and atmospheric pressure.

Several methods have been used in the preservation of maize [12-16] some of which are drying and storage crib; mud or cement-plastered basket; brick bin; ferrocements bin (Ferrumba); postcosecha galvanized steel silos; in the modern-day technology, refrigeration system also can be used because it can be manipulated to give various conditions.

Charles and Rogers [17] observed that overnight storage of fresh maize in wagon or truck can have a marked effect on their future storability. Akintunde and Obadina [11] developed a refrigeration system for the storage of pepper and tomatoes which provide artificial conditions under which this product can survive for a long period of time. The system is able to store 20 kg of produce at a temperature range of 2.5 and 4.4 0C with a relative humidity of 0.97 and 0.98. Ajayi [11,18] performed an evaluation on an air blast freezer for the storage of fruits and vegetables which can handle 20 kg of fresh fruits and vegetables with a capacity of 0.83116 kW and it is capable of storing samples for 14 days. Mogaji and Fapetu [19] developed an evaporative cooling system for the preservation of fresh vegetables for extending the shelf life of tomatoes and carrots, with temperature varying between 16 and 25ºC. This temperature was constantly below ambient. This system extended the shelf life by fourteen days relative to ambient [3,20]. This research focuses on one of the perishable produces (maize) which may lose half of its initial sugar content in one day at 21ºC and could be contaminated by microorganisms or insects in less than three days of storage in ambient conditions.

The project aims at storing and preserving the quality of fresh maize for ten days. The specific objectives of this study are to develop a refrigeration system to meet preserve fresh maize and evaluate the performance of the system constructed.

2. METHODOLOGY

In the design of the refrigeration system for maize preservation, some parameters were considered in the determination of total refrigeration load. These parameters include the incoming temperature of the product, the incoming relative humidity of the product, the temperature and humidity of the environment. The refrigeration system designed to accommodate fifteen kilograms (15 kg) of freshly harvested maize. It was designed to have three pallets on which the maize ears were arranged for proper air circulation to each of the maize ears stored.

2.1 Design Analysis of Machine Components

2.1.1 Determination of bulk density of maize at harvest

In other to design the refrigeration system for the storage of fresh maize, the needed volume was determined using an empirical formula developed by Bakker, et al. (1999), which relates bulk density and moisture content of maize as stated in Equation (1).

$$TWm = 0.7019 + 0.01676\ Mwb - 0.0011598\ Mwb2 + 0.00001824\ Mwb3 \quad (1)$$

Where TWm= bulk density and Mwb= moisture content of maize.

Maize harvested at maturity normally has an average moisture content range between 30 and 32% (wb) [2,21]. The bulk density of the maize ears was calculated to be 648.3 kg/m3. For the purpose of better air circulation in the system, the dimension of the refrigeration system was taken as 0.65 m by 0.65 m by 0.70 m. The wall thickness was taken to be 12 mm to accommodate the insulating material.

2.2 Determination of Cooling Load Capacity

The cooling load and refrigeration hardware required for an application are determined by several factors. These include field heat removal, respiration heat removal from the product, and the heat gained from outside the cold space. Accurate determination of the cooling load is necessary for the selection of equipment having adequate capacity to efficiently cool and maintain the proper temperature and humidity levels in the storage. The heat which usually evolves from different sources was summed up. The heat sources to be considered in this design.

Transmission Load (TL) is the heat transferred into the refrigerated space through the surface of the refrigerated space. Heat is gained and lost through the refrigerator's floor, walls, and ceiling by conduction. Conductive heat gain or loss is computed from equation (2) and (3) and Fig. 1 shows the cross-section of the refrigeration wall.

$$Q = UA\ (\Delta T) \quad (2)$$

$$U=1/(1/ho+(L_A)/(k_A)+L_B/k_B+L_C/(k_C)+1/hi) \quad (3)$$

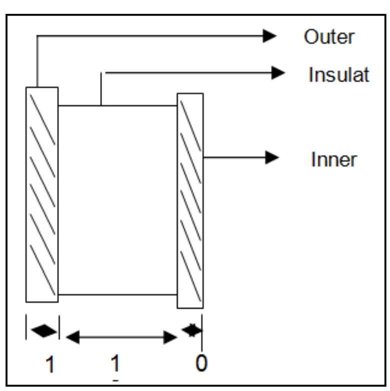

Fig. 1. The cross-section of the refrigeration system walls

The material used for wall, lagging and inside surface of the refrigerated space is mild steel, glass wool and stainless steel respectively. Their properties are shown in Table 1.

Q is sensible heat gain (watts), U is overall heat transfer coefficient (W/m2K), A is the surface area of the cooled space = 2.05 m^2, ΔT = cooling load temperature difference in ºC T_i= inside temperature (ºC); To=outside or ambient temperature 30ºC; ho=11.6 W/m^2K; hi=14.5 W/m^2K; LA=0.001 m; L_B=0.012 m; LC=0.0006 m; k_A= 46.5 W/mK; k_B= 0.046 W/mK; k_C=16.20 W/mK; To= 0 - 2.5ºC; Ti=27ºC.

Putting these values in equations 3 and then equation 2, the value of Q was estimated to be 113.3 W.

Product Load (PL) which varies with location and harvesting time. The initial product temperature and the final product temperature were considered for estimating the refrigeration requirement. Heat gains associated with air entering the refrigerated space as a result of opening (infiltration air). Field heat represents the cooling necessary to reduce the product from harvest temperature down to the safe storage level. The product load is the summation of field heat load and respiration load which was computed from Equation (4) and (5) respectively.

$$Q_1 = mc\Delta T \qquad (4)$$

$$Q_1 = MK \qquad (5)$$

Where

Q_1 = field heat load, kJ; m = mass of product cooled per 24 hours, kg,; c = specific heat of maize = 1.8 kJ/kgºC; $\Delta T \;= T_0 - T_1$ (temperature drop of product in 24 hours), °C; Q2 = respiration heat load, W; M = mass of product cooled per 24 hours, tons; and K = rate of respiratory heat production, kW/ton. day = 15.87 kW/ton.day

Q_1 = 6.09 W and Q_2= 8.60 W

$P_L = Q_1 + Q_2 = 14.69W$

Infiltration Load (IL) which is the heat transferred by the mixture of outside air with the inside environment. These convection heat gains are high during summertime loading and minimal when the cabinet is closed and calculated using equations (6) and (7).

Door infiltration (m3/min) qd = (door openings/hr x factor from table)/60 (6)

$$I_L = qT\rho\mathrm{h} \qquad (7)$$

Where ρ = density of air and h = enthalpy of air = (cpat)

Assuming the door opens 10 times per hour and a factor of a light door is 2.0 per maize

IL = 3.84 W

Total Cooling Load (Qt) is a function of TL, PL, and IL. The individual heat gains are added and computed from equation 8 and 9 to find the total heat gain for a cold storage.

$$Capacity = Qt \times SF \qquad (8)$$

where Qt = calculated total heat gain, W,

$$Qt = TL + P_L + I_L = 117.64W \qquad (9)$$

The factor of safety is between 5 % and 10%, taking a 10% factor of safety

SF = service factor = 1.1

Capacity = 129.40 W=1⁄6 hp

Plant capacity is 1⁄6 hp.

2.3 Refrigeration System and Equipment Selection

Vapour Compression refrigeration system was used because it is widely used in commercial and industrial applications. The vapor-compression uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects the heat elsewhere. All such systems have four major components: A compressor, a condenser, a thermal expansion valve and an evaporator. Circulating refrigerant enters the compressor in the thermodynamic state known as a saturated vapour and is compressed to a higher pressure, resulting in a higher temperature as well. The hot, compressed vapour is then in the thermodynamic state known as a superheated vapour and it is at a temperature and pressure at which it can be condensed with cooling air. The hot vapour is routed through a condenser where it is cooled and condensed into a liquid. This is where the circulating refrigerant rejects heat from the system and the rejected heat is carried away by air.

Table 1. Properties of materials for the refrigeration wall design

Material	Density, ρ, (kg/m^3)	Specific heat, $c_{p,}$ (J/kg.)	Thermal conductivity, k,(W/m.K)
Mild steel	7 753	456	46.50
Stainless steel	803	500	16.20
Glass wool	64 – 160	4090	0.046

S/N	Parts	Qty
1	Bottom Cover	1
2	Compressor	1
3	Compressor Cutout	1
4	Condenser	1
5	Door	1
6	Expansion Valve	1
7	Pin	3
8	Pin Screw	12
9	Pin Support	12
10	Frame –Insulation	1
11	Hidge	2
12	Lining	1
13	Roll-back Evaporator	1
14	Support	4
15	Support-screw	16
16	Tank	1
17	Top Cover	1

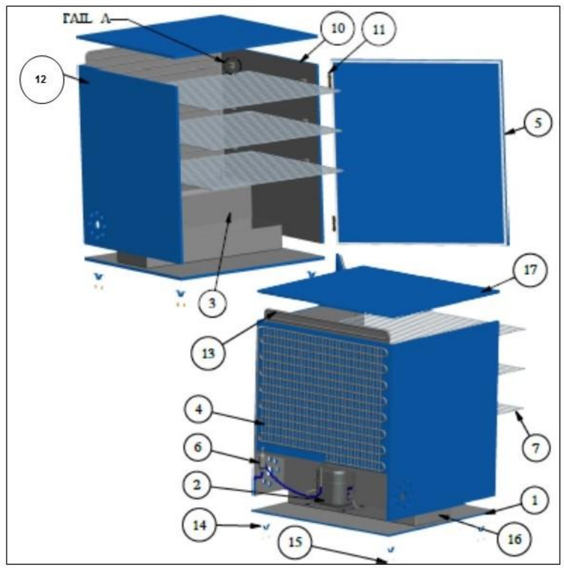

Fig. 2. Assembly drawing of refrigeration designed

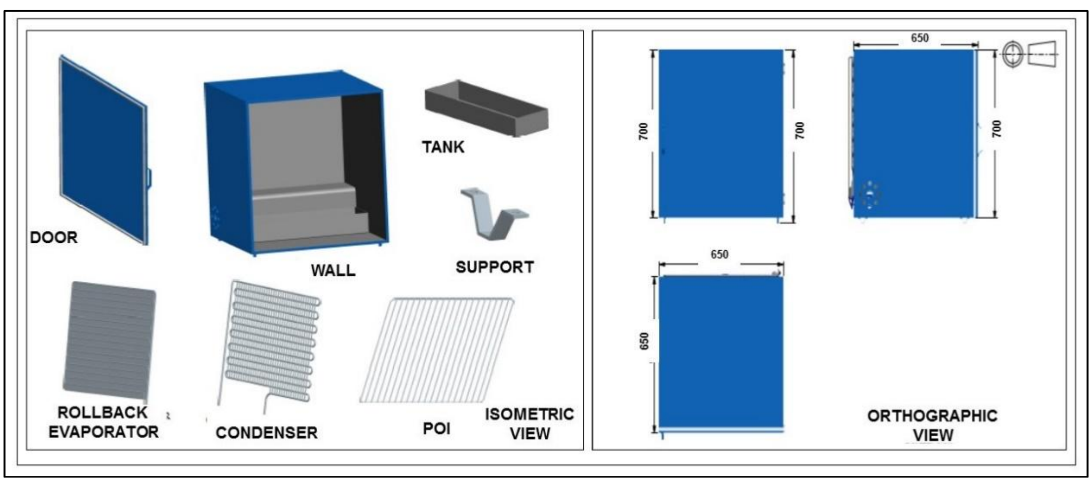

Fig. 3. Component view of the system design

In this work, R134a was used as the working. R134a (Tetrafluoroethane) was used because of its availability, friendliness to the ecosystem. Figs. 2 and 3 show the Isometric and Components Views of the design made for the refrigeration system.

2.4 Assembly of Refrigeration System

The various parts of the refrigeration system assembled viz: the inner wall, the outer wall, the upper and bottom plates. The insulation material was held in place between the two walls with the aid of the chemical gum. After proper installation of the insulation material, the bottom and the upper plates were fixed in place. The compressor, condenser, and dryer were installed at the rear side of the system wall.

The refrigeration door seal was installed on the door using the chemical gum to hold it in place and the door hinges were riveted to the door and to the wall of the refrigeration system hence making the system hermetic. The pallets were arranged in their respective positions on the pallet stands which had been riveted to the inner wall of the system. The outer wall was painted. Then refrigerant R134a was charged into the system and the system was tested again for any leakages and all leakage detected were corrected. Loading and offloading can be done easily on any pallet of choice. The machine can be operated by a single person.

3. RESULTS AND DISCUSSION

The designed refrigerating system was constructed and tested under two conditions; no-load and load conditions. During the experimentation, both the temperature in the system and the relative humidity were measured. The measured data were used for further evaluation of the system in a no-load condition attained a temperature of 0ºC after eight hours. This temperature was relatively maintained by the system. A little fluctuation between ±10ºC was experienced due to varying atmospheric conditions. The average of the daily test performed for 5 days is shown in Figs. 4 and 5.

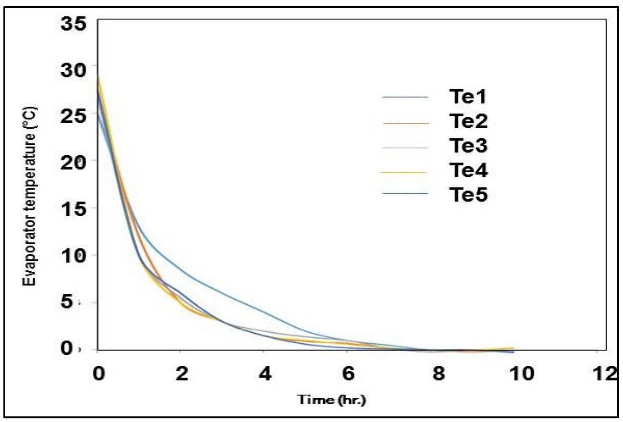

Fig. 4. Daily variation of evaporator temperature with time on no load (Te1, Te2, Te3, Te4 and Te5 are evaporator temperature for day 1, 2, 3, 4 and 5 respectively)

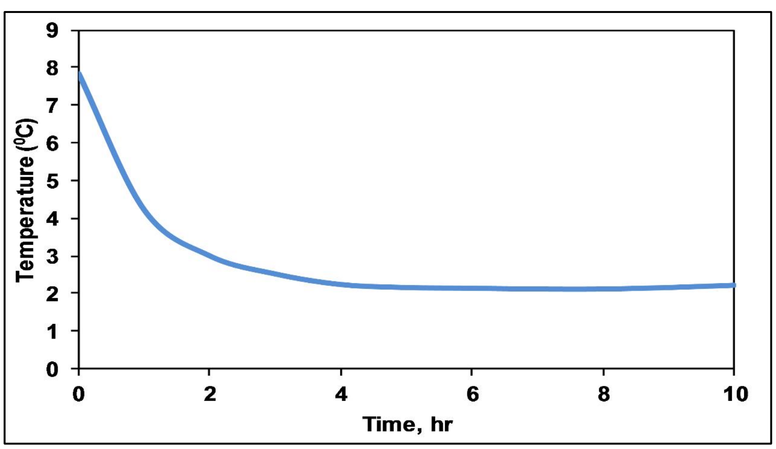

Fig. 5. Average variation of temperature with time on no load condition (where Te1, Te2, Te3, Te4, and Te5 are evaporator temperature for days 1, 2, 3, 4 and 5 respectively)

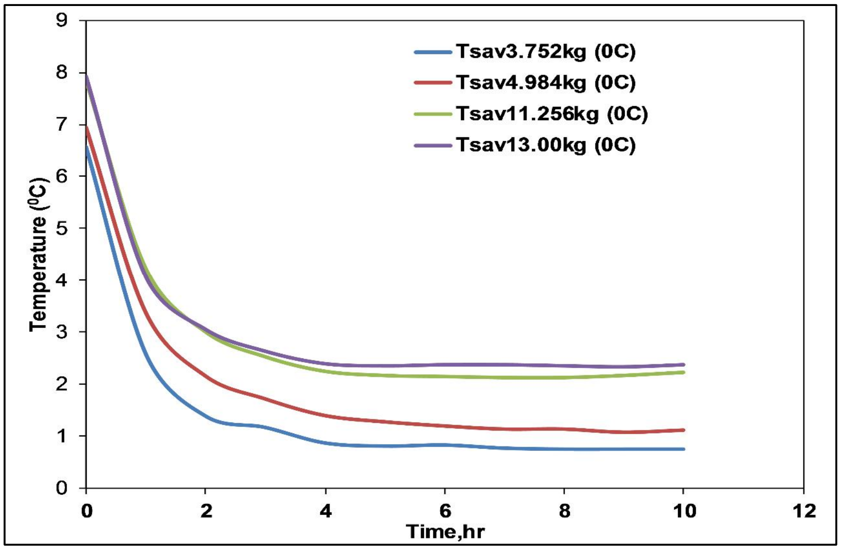

Fig. 6. Variation of average cold space temperature with time on loading conditions

The system was also tested with 3.752 kg, 4.984 kg 11.256 and 13.00 kg load of fresh maize. The system's relative humidity and temperatures were observed and recorded (appendix 1). The system attained a temperature between 2 and 2.5ºC after five hours; this is less than the design range of 8 to 10 hours. When loaded with 13.00 kg of fresh maize the system maintained a relatively constant temperature of 2.5ºC and it maintained this temperature throughout the experiment. In each case, the system was run for ten days. Within the period of experimentation, there was no noticeable significant change in the colour, texture and taste of the fresh maize kept in the system. This shows that the system can be used to store fresh maize up to 13 kg for a minimum of ten days. This can be justified by the added factors as indicated in equation (8).

4. CONCLUSION

In this work, the storage conditions of the fresh maize were identified as: temperature ranges between 0°C and 2.5°C and a relative humidity range between 90 and 95%. Based on these storage conditions a refrigeration system was designed using the vapour compression refrigeration cycle and refrigerant 134a as the working fluid. A compressor of 1/6 hp was selected using design results and other major components which include an evaporator, condenser, and control system. The load estimation was based on many factors which include transmission load, product load and infiltration load. The fabricated system was achieved based on the design calculations. The refrigeration system developed is a simple technology that can easily be operated. The system constructed is capable of preserving fresh maize ears for ten days. The system was designed to accommodate 13 kg of fresh maize and to maintain it at the temperature range between 0ºC and 2.5ºC and relative humidity ranges between 90 and 95%. The test result indicated that on "no-load" the system is capable of maintaining a temperature between ±1ºC after eight hours of operation. Also, the system can store up to 13 kg of fresh maize for 10 days based on the experiment carried out in this work.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX 1

Temperature and relative humidity measuring for 2 days with loading and no loading

Day 1

Time, t (hr)	Te (0C)	Ts (0C)	Tc (0C)	Ta(0C)	Rha (%)	Rhs(%)
0	0	30	50	27	70	92
1	0	12	63.2	27	68	92
2	-0.5	6	61.6	27	68	92
3	0	4	60.9	28	66	92
4	-1	2.5	62.3	28.5	69	93
5	0	2	66	29	68	93
6	0	1.6	64	30	68	92
7	0	1.5	63.5	28.8	63	90
8	0	1.5	64.8	28	55	90
9	0.1	1.5	66.7	27	58	91
10	0.2	1.5	68.4	27	54	91

Day 2

Time, t (hr)	Te (0C)	Ts (0C)	Tc (0C)	Ta(0C)	Rha (%)	Rhs(%)
0	0	1.2	63.2	28	63	92
1	0	1.4	61.6	28.5	55	92
2	0.9	1.3	60.9	29	58	92
3	0	1.3	62.3	30	54	92
4	-1	1.2	66	28.8	70	93
5	0	1.2	64	28	68	93
6	0	1.2	63.8	27	68	92
7	0	1.1	54.8	27	66	90
8	0	1.1	56.7	27	69	90
9	0.1	1.1	58.3	27	68	91
10	0.6	1.1	53	27	68	91

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