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DESIGN AND CONSTRUCTION OF HYDROCOOLING CHAMBER FOR FRUITS AND VEGETABLES STORAGE

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Abstract
Fruits and vegetables harvested at either physiological or commercial stages have very short shelf life as the fruits usually ripen within a week while the vegetables shrivel few hours after harvest, if they are not appropriately stored. Reports have shown up to 70% losses for both commodities under natural tropical conditions (30±2°C and 70±2% RH) when not well handled and stored. Unfortunately, tropical fruits and vegetables are adversely affected by cold temperatures below 12°C as they are prone to chilling injury, hence limiting the use of refrigeration in storing the fruits fresh. Moreover, most of the storage methods available in the developed temperate countries such as Controlled Atmosphere Storage, Hypobaric, Irradiation etc. are either too expensive or technically sophisticated to be adopted for tropical fruits and vegetables. This study was therefore conceived and undertaken to develop a novel Dome-like Hydro-cooling Chamber kitted with Solar Energy powered Water-Cooling System, to maintain the temperature and humidity of stored fruits and vegetables at about 15°C and 85% RH respectively. Utilization of solar energy is due to irregularities and high costs of electricity in the developing nations including Nigeria.Preliminary results have shown that the dome-shaped structure with a cuboidal base of 7m x 4m x 2.5m and a dome top central height of 1.5m constructed with a non-hollow cement blocks of average weight of 23kg with dimensions of 0.46m x 0.23m x 0.15m and kitted with a solar energy powered water cooling system at about 10°C can achieve the storage conditions of about 15°C and 85% RH holding up to 28 metric tonnes of plantain fruits.

Keywords: *Hydro-cooling chamber, Water Cooling System, Solar Energy, Storage, Fruits and Vegetables.*

1.0 Introduction

Fruits are the succulent or fleshy covering of nuts which are pulpy in character and often juicy. Since they develop from flower of plants, they consist of the ripened seed or seeds with some edible tissues attached while vegetables are the leafy outgrowth of plants used as food and include those plants and parts of plants used in making soups or served as integral parts of the main sources of meal (Ihekoronye and Ngoddy, 1985).

Fruits and vegetables are similar in composition; contain high percentage of water averaging 85%, with fat and protein in very small and varying amounts (Oluwalana, 2010). A considerable proportion of their carbohydrates are present as cellulose, starch (in small quantity) and sugar, while peptic substances form the intercellular cement layer of the fruits (Oluwalana, 2010). The firm structure of the under-ripe fruit is probably due to the presence of these peptic substances in the form of insoluble calcium salts of pectic acid which are decomposed during ripening process into water soluble pectin (Wills *et al*., 1981; Oluwalana, 2010). Fruits and vegetables are usually harvested either at physiological or commercial maturity stage and once harvested, they have very short shelf life, as most fruits ripen quickly (George, 1981; Olorunda and Aworh, 1984) while most vegetables become shriveled or desiccated and quickly deteriorate if not properly stored (Wills *et al*., 1981).

Losses of more than 70% of fruits and vegetables have been reported at various points in their distribution system in Nigeria (Olorunda *et al*., 1978, Oluwalana, 2018). This has been attributed to poor post-harvest handling practices and lack of appropriate storage facilities and or technologies, which result in substantial part of the crops becoming damaged or completely unsuitable for human consumption by the time they reach the ultimate destination or consumers. This obviously deprives the consumers of numerous micronutrients, richly endowed in these commodities (Oluwalana, 2010; 2018). Refrigeration, air conditioning, controlled atmosphere storage (CAS), modified atmosphere storage (MAS), hypobaric storage, chemical treatment, hot water dip, irradiation and their combination/hurdle treatments were reported for extending the green and storage life of fruits and vegetables (Oluwalana, 2010; 2018; Majidi *et* al., 2014; Patel *et al*., 2015). The associated disadvantages of these technologies are their electricity-dependence, complexity and high cost; therefore, making them unsuitable in less technologically developed countries such as Nigeria (Olorunda *et al.,* 1978; Oluwalana, 2010). Other problems associated with these methods are chilling injury and dehydration (Aghdan and Bodbodak, 2014;

Jin *et al*., 2014). Hence, there is need for the development of hydro-cooling storage system, which will prevent desiccation, slow down respiration and thereby delay ripening and deterioration of these low temperature sensitive commodities

.2.0 Materials and Methods

2.1 Materials and Equipment

The building materials (cement, stones dust and sand) used in putting up the hydro-cooling chamber were locally sourced from Akure, Ondo State, Nigeria. The lagged door and window were made from galvanized steel while 12 mm cast iron rod was used in reinforcing the decked top of the chamber. A 5 mm thick wired glass was used for the 4 small lighting windows.

2.2 Methodology

Brief Description of the Hydro-cooling Chamber

The hydro-cooling chamber is domelike in shape. This is to allow for better air circulation at the top. The base was cuboidal in shape, with 4 small lighting windows and 2 small humidity control exhausts. The chamber was lined with 2 inches (5cm) diameter stainless steel pipes that would transport cooling water round the room, thereby removing excess heat generated.

Design Analysis

Determination of the Required Volume of Hydro-cooling Chamber:

The cooling chamber is designed against 28 tonnes of plantain fruits, (using plantain fruits as reference for the design).

Density of plantain =
614 kgm^{-3} (Falade and Oyeyinka, 2014);

Volume occupied =
weight / density = 28 tonnes /614 kgm^{-3} = 45.6 m^3

To give room for air space, passage and selves, half of the chamber is assumed to be utilized by fruits. This implies that the needed volume of the chamber =
2 x 45.6 m^3 = 91.2 m^3

Therefore, the cuboidal base of the chamber was calculated to be 7 m by 4 m by 2.5 m and the dome top being 1.5 m high, at the Centre, and rest on the 7 m long wall. This gives:
Volume of the cuboid = 70 m^3
Volume of the dome top = 24 m^3
Total volume of the chamber = 94 m^3

Determination of Total Heat Load of the Hydro-cooling Chamber:

The maximum heat load of the chamber was calculated based on the thermal and physical properties of the products to be stored.

Properties:
Thermal conductivity of concrete = 0.87 Wm^{-1}K^{-1};
Thermal conductivity of fruits = 0.9 Kcal/ton/hr.
Specific heat of the fruits = 3778 Jkg^{-1}K^{-1};
Average heat of respiration of fruits = 10.4167 kcal (ton^{-1}hr^{-1}) = 6.39 Watts/ ton;
Weight of the stored fruits (x) = 614 kgm^{-3} x 47 m^3 (assume half volume of chamber is stored with fruits) =28,858 kg = 28.858 tons;
(1) Heat of respiration from fruits =
28.858tons x 6.39 Watts/ton
= 184.4kW

(2) Intake heat:
This is the heat that will be released from the fruits to cool down from field to storage temperature (Hp) =mcΔT

It is assumed that 20% of the storage load will be supplied daily and cooling to storage temperature will take place in two days

$$\frac{5600 \times 0.9 \times (27-15)}{2 \times 24} = 1{,}260 \text{ kCal/hr.} = 1{,}465 \text{ Watts} = 1.5 \text{ kW}$$

(3) Heat loss through concrete walls and roofs =

$$\frac{0.87 \times A\,(Ta - Tc)}{hc}$$

$$= \frac{0.87 \times 120.08\,(32-15)}{0.06} = 29.6\text{kW}$$

(4) Total heat load =
{184.4 + 29.6 + 1.5} kW = 215.5 kW
where A = total area of concrete floor, walls and roof
= 28 + 2(13.42) + 2(17.5) + 7(4.32)
= 120.08m^2;
T_a = ambient temperature of the chamber = 32° C
T_c = final temperature of the fruits (15° C)
h_c = concrete thickness = 0.06 m
h_p = average heat of respiration of people curved length of the dome = 4.32 m
Allowing for standing time of 6hrs. per day, water cooling unit was selected to have capacity of:

$$\frac{215x4}{3} = 287 \text{ kW}$$

Cooling Water Rate

The cooling water rate for the removal of excess heat from the storage chamber based on 3 cases, that could be adjusted, are presented in Table 1 . The cooling water rate is calculated based on lighting of and personnel inside the chamber, and the amount of products stored in the chamber.

Case 1: No lighting and personnel in the chamber (H_p = 0)
{mp + 29.6} + Hp kW =m_w x 4.186 x (Tc - Tw) =
m_w x 4.186x(15-10)Kw

where m_p = mass of product stored in the chamber,
m_w = mass rate of the hydro-coolant (kgs^{-1}), and
T_w = temperature at which the hydro-coolant enters the chamber.
T_c = final temperature of stored fruits.

Case 2: One personnel with no bulb lighted in the chamber Assuming a person produced 240W of heat in a day. Therefore, for time spent in the chamber;

$$\{mp + 29.6\} + \frac{0.240}{24 \times 3600}\ kW = m_w \times 4.186 \times (15 - 10)\ kW$$

Case 3: One personnel with one 26 Watt-bulb lighted in the chamber

$$\{mp + 29.6\} + \frac{0.240}{24 \times 3600} + 0.026kW = m_w \times 4.186 \times (15 - 10)\ kW$$

Note: In all the cases, either m_w or T_w could be manipulated to have a sustained temperature of 15^{0}C in the chamber.

Table 1: Cooling water rates for chamber with a personnel, no lighting and with a personnel and lighting

Products (tons)	Heat load (kW) (1)	Cooling water rate (ltr/s) (1)	Heat load (kW) (2)	Cooling water rate (ltr/s) (2)
1.0	35.99	1.7195	36.016	1.7208
2.0	42.38	2.0248	42.406	2.0261
3.0	48.77	2.3301	48.796	2.3314
4.0	55.16	2.6355	55.186	2.6367
5.0	61.55	2.9408	61.576	2.9420
6.0	67.94	3.2461	67.966	3.2473
7.0	74.33	3.5514	74.356	3.5526
8.0	80.72	3.8567	80.746	3.8579
9.0	87.11	4.1620	87.136	4.1632
10.0	93.50	4.4673	93.526	4.4685
11.0	99.89	4.7726	99.916	4.7738
12.0	106.28	5.0779	106.306	5.0791
13.0	112.67	5.3832	112.696	5.3844
14.0	119.06	5.6885	119.086	5.6897
15.0	125.45	5.9938	125.476	5.9950
16.0	131.84	6.2991	131.866	6.3003
17.0	138.23	6.6044	138.256	6.6056
18.0	144.62	6.9097	144.646	6.9109
19.0	151.01	7.2150	151.036	7.2162
20.0	157.40	7.5203	157.426	7.5215
21.0	163.79	7.8256	163.816	7.8269
22.0	170.18	8.1309	170.206	8.1322
23.0	176.57	8.4362	176.596	8.4375
24.0	182.96	8.7415	182.986	8.7428
25.0	189.35	9.0468	189.376	9.0481
26.0	195.74	9.3521	195.766	9.3534
27.0	202.13	9.6574	202.156	9.6587
28.0	208.52	9.9627	208.546	9.9640
28.9	214.00	10.2247	214.0286	10.2259

Construction of the hydro-cooling chamber

The chamber was supported by six reinforced pillars; three on each side of the 7 m wall, and the concrete floor was about 6 cm thick to reduce heat transfer through the floor. The pictorial views of the chamber are shown in Figures 1 – 5. Non-hollow concrete bricks were made at the site with proper finesse using a mixture of thirteen head pans of sand, seven head pans of stone dust and 50 kg cement. Each brick/block have an average weight of 23 kg with dimensions of 0.4572 m by 0.2286 m by 0.1524 m; approximately 1,444 kg /m^3. The picture of a sample of the molded brick is shown in Plate 1 below. The non-hollow bricks serve as strong insulator, preventing outside heat entering into the chamber.

Determination of Ambient Conditions:

The ambient conditions (temperature and humidity) of the empty chamber were measured using Digital-Davis Postharvest Pocket Thermometer (Delta Trak Needle Probe Thermometer, USA; Model 11065; Accuracy C 1°±) and Max-Min Thermo-Hygrometer (Model HH439, China; Accuracy 1±%)

Plate 1: The Non-Hollow Block (Weight of 23kg with dim ...).23m x 0.15m).

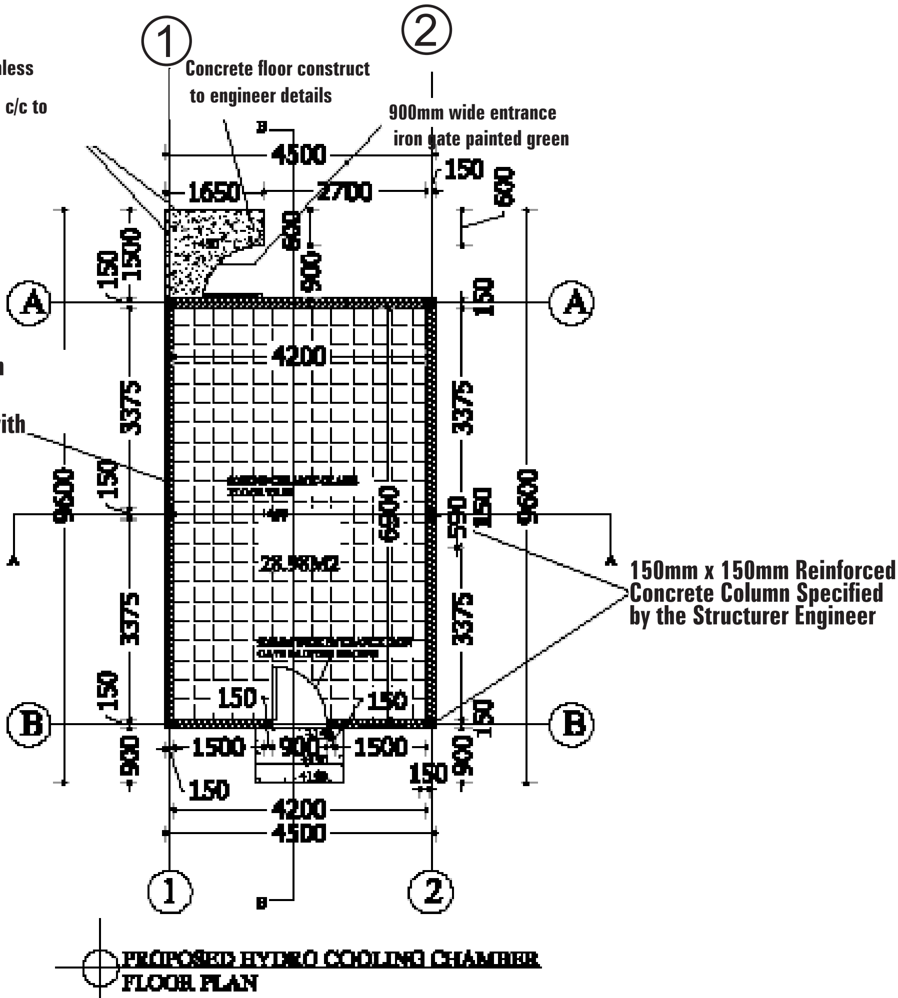

Figure 1: The Plan Features of the Hydro-Cooling Chamber

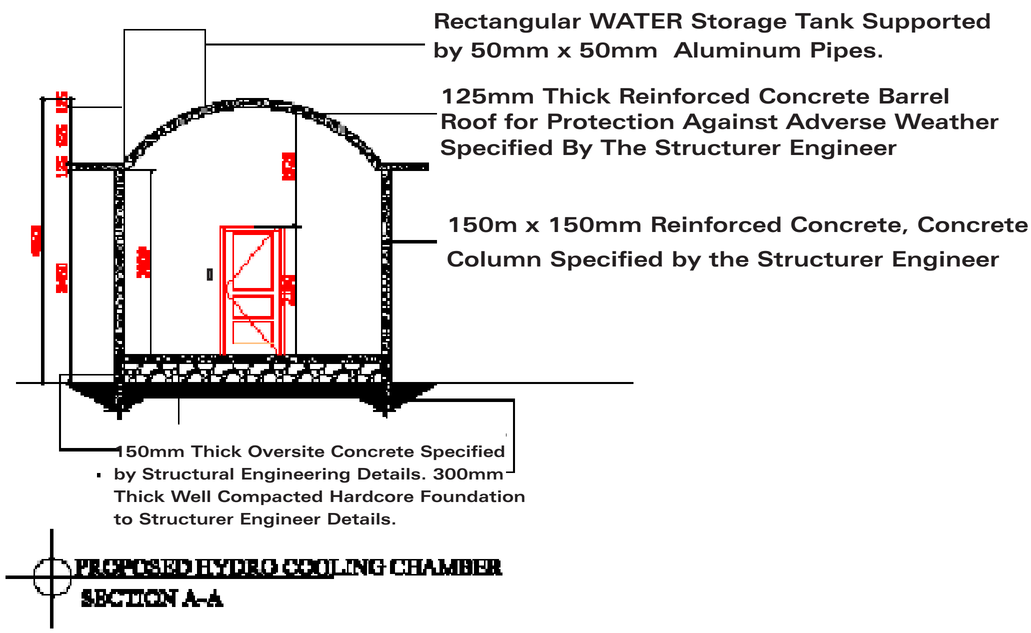

Figure 2: The Front View of the Hydro-Cooling Chamber

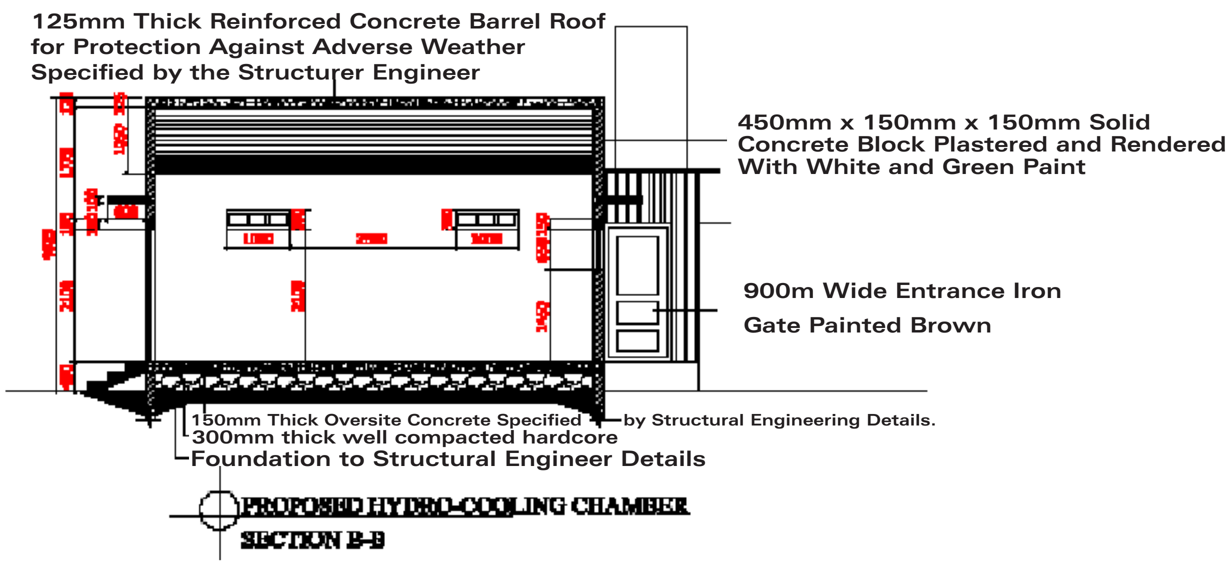

Figure 3: The Side View of the Hydro-Cooling Chamber

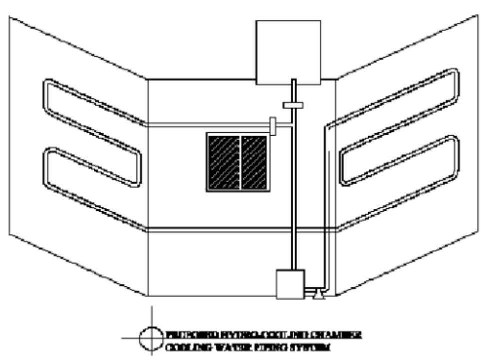

Figure 4: Cold Water Circulatory System within the Chamber

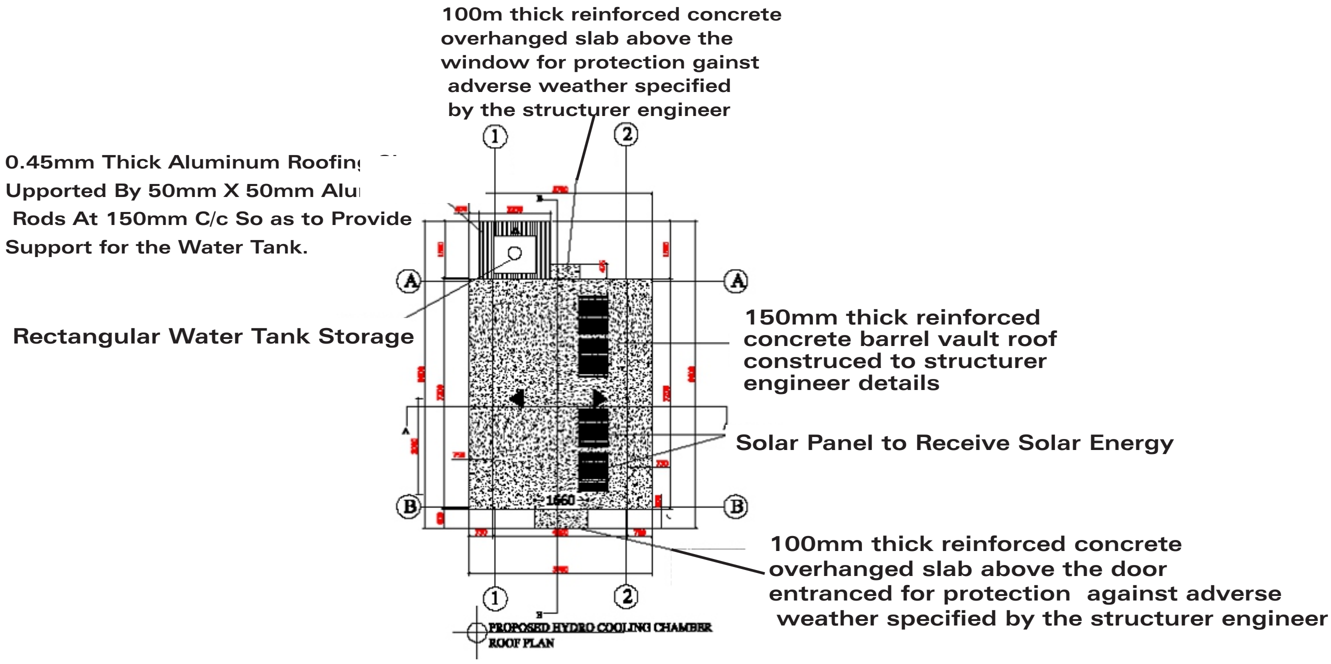

Figure 5: The Roof Plan of the Hydro-Cooling Chamber

3.0 Results and Discussion

The ambient conditions (temperature and humidity) of the empty chamber were 23 °C and 49% respectively while the outside conditions in December were 34 °C and 52% RH respectively. These average values were obtained from measurements taken at 6 hourly intervals for 3 days. The lower temperature and humidity recorded inside the chamber could be as a result of the non-hollow bricks (Plate 1) used for the construction, which insulate the room from the higher atmospheric temperature and humidity. However, there is very scanty information on variant to this in the literature for comparison. This helped in reducing the amount of cooling water needed to be transported through the system to achieve the desired storage temperature and humidity taking into considerations the thermal properties of materials utilized and certain assumptions. A storage temperature of 15 °C and humidity of 85% were achieved by running the cold-water system at 10 °C for 20 minutes.

There was a good air circulation at the top of the chamber due to the dome-like shape of the concrete roof with sufficient head space as stipulated in the materials and methods section above (Figures 2 & 3). There was also an effective heat transfer of the cold water transported round the inside of the chamber through the concentric 2 inches (5cm) diameter stainless steel pipes (Fig. 4). Intermittent venting of respiratory gases particularly carbon dioxide and ethylene on 12 hourly basis through the use of the 2 small humidity control exhausts prevented the accumulation of ethylene gas in the chamber, which could have hasten the ripening of the stored fruits.

The heat loads by stored commodity and the corresponding cooling water rates required (Table 1) were observed to increase with increase in the volume (tons) of fruits stored in the chamber. These changes did not however vary significantly with the three scenarios of operating the chamber: (i) without personnel who is assumed to generate 240 Watts of heat inside and no lighting bulb (26 Watts) activated ; (ii) with personnel but no lighting bulb there was no variation in conditions (i) and (ii) and (iii) with personnel and a lighting bulb activated . In all the cases, either the mass rate of the hydro-coolant (m_w) or the temperature at which the hydro-coolant (T_w) enters the chamber was manipulated to have a sustained temperature of 15 °C in the chamber. Moreover, the non-hollow bricks used in constructing the chamber, the dome-like concrete top, the lagged door, lagged window and the 5 mm thick wired transparent glasses for the 4 small viewing windows all served as strong insulators, minimizing the penetration of the outside heat into the chamber.

Results obtained have shown that the Hydro-cooling chamber can achieve the storage conditions of about 15°C and 85% RH while delaying ripening and thereby extending the shelf-life of the plantain fruits for up to 2 weeks. Similar delay in ripening and extension of shelf-life have been reported by Oluwalana (2010 and 2018) in his study of plantain fruits either treated with Semperfresh food surface coating or wrapped in 25-30µm polyethylene film bags stored at tropical ambient conditions (28±2°C and 70±5% RH).

4.0 Conclusion

The purpose for which this project was conceived (i.e. to develop a novel Dome-like Hydro-cooling Chamber kitted with Solar Energy powered Water-Cooling System as an alternative to electricity) has been partly achieved. The utilization of solar energy is due to irregularities and high costs of electricity in the developing nations including Nigeria.

Preliminary results have shown that the dome-shaped structure with a cuboidal base of 7m x 4m x 2.5m and a dome top central height of 1.5m constructed with a non-hollow cement blocks of average weight of 23kg with dimensions of 0.46m x 0.23m x 0.15m and kitted with a solar energy powered water cooling system at about 10°C can achieve the storage conditions of about 15°C and 85% RH holding up to 28 metric tonnes of green plantain fruits for 2 weeks before ripening. This is in comparison to the 3-5 days shelf-life achievable with the convectional ambient (28±2°C and 70±5% RH) storage (Control). This hydro-cooling chamber, to a great extent could therefore be an adoptable technology in the tropical developing countries including Nigeria, to store fresh fruits and vegetables in order to keep them fresh and also extend their shelf lives.

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