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Article

Temperature characteristics of a wood-insulated refrigeration system for chilling and preservation of agricultural products

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Abstract: The scarcity of the insulators that are required for refrigeration has made it necessary to use locally available materials that can achieve the desired refrigeration. This work presents the performance evaluation of a refrigerator utilizing a locally available material, which is wood particles that have been converted to particle board, as one of its insulators. A vapor compression refrigeration system was designed and fabricated to chill and preserve agricultural products, which are eggs, yogurt, and tomatoes. The various temperatures at which the agricultural products became chilled were compared with their theoretical preservation temperatures obtainable in literature, thereby evaluating the performance of the refrigerator. The temperature of 11 °C, which was recorded for the egg in the present experiment, is lower than the theoretical preservation temperatures of 18 °C to 21 °C for an egg. The temperature of 7 °C, which was recorded for the yogurt, is approximately equal to its theoretical preservation temperature of 5 °C. The temperature of 8 °C, which was recorded for the tomato, is lower than the theoretical preservation temperatures of 7 °C to 10 °C of tomato. This work has revealed that wood particles have the potential to achieve refrigeration, as well as chill and preserve agricultural products.

Keywords: temperature; refrigeration system; insulator; locally available material; chill; preservation

1. Introduction

In the current era of food scarcity, preservation of agricultural products cannot be set aside, as preservation, according to Jayaraman and Das-Gupta [1], allows better storage life and appreciable reduction of losses at a time of storage of agricultural products by delaying microbial, chemical, and physical processes that lead to food deterioration.

Refrigeration, which is the process of maintaining the temperature of a closed chamber to a value that is less than that of its environment, is one of the means of preservation of agricultural products [2]. During refrigeration, heat is removed from the closed chamber and agricultural products therein (which is at a lower temperature) to its surroundings (which is at a higher temperature). The removal of the heat makes the temperature of the chamber and agricultural products to be reduced and, therefore, cools the agricultural products [2,3]. A refrigerator, which is a device that can be used to carry out refrigeration, should be designed such that it will be able to cool agricultural products to a required temperature that will preserve the products.

The types of refrigerators are air refrigerators, vapor compression refrigerators, vapor absorption refrigerators, thermoelectric refrigerators, and cascade refrigerators [2,4]. Air refrigerator is one of the earliest devices used for cooling. It became obsolete because of its low coefficient of performance and high operating cost. Absorption refrigeration is referred to as a heat-operated system because it is driven by thermal energy through a generator [3].

A vapor compression refrigerator utilizes a mechanical compressor with the aid of a working fluid to transfer the heat from a space of lower concentration of temperature to another space of a higher concentration of temperature. It depends on the evaporation of the working fluid for its operation. In addition to the compressor, it makes use of an evaporator, a condenser, and an expansion valve. The working fluid changes phases as it moves around the cycle [2]. **Figure 1** shows the removal of heat (Q_R) by a vapor compression refrigerator from a space of a lower concentration of temperature (T_1) to a space of a higher concentration of temperature (T_2), and the work (W) that is done by the compressor on a working fluid.

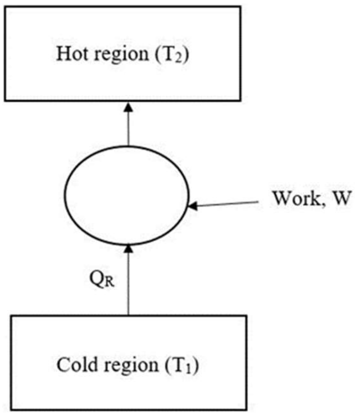

Figure 1. The removal of heat by a refrigerator from a lower to a higher temperature region [2].

The first step toward artificial means of refrigeration was discovered in the sixteenth century when sodium nitrate or potassium nitrate was added to water to cool the temperature to create a sort of refrigeration bath for chilling wine [5]. The first mechanical refrigeration machine, which was proved to be successful on an industrial scale, was developed by James Harrison in 1857. The machines were capable of producing ice or cooling brine [5,6].

Insulation plays a vital role in the effective operation of refrigeration systems, and there exist various advancements in insulators used in refrigerators. Some of them include aerogel [7], polystyrene foam [8], glass wool [9–11], thermocol [11], as well as vacuum insulation panels, polyurethane foam, polyethylene terephthalate foam, and natural fiber insulation [12]. Vacuum insulation panel is made up of a core material surrounded with a gas-tight barrier, minimizing heat transfer, and thereby leading to good insulation. Polyurethane foam insulation has high thermal resistance. Its thin insulation layers without sacrificing performance are a result of its recent improvements in its formulation. Natural fiber insulation, such as hemp or cotton, offers alternatives to conventional synthetic insulation materials, contributing to good performance efforts in refrigeration industries. Aerogel is lightweight materials with extremely low thermal conductivity, and offer the potential for superior insulation performance in a compact form factor. Polyethylene terephthalate foam is a lightweight and environmentally friendly insulation material that has good potential application as thermal insulation in refrigeration systems [12–14].

As a result of the importance of refrigeration in residences, industries, and offices, the use of refrigeration to maintain a chamber to a temperature that is less than that of its immediate environment has received much attention, and several works have, because of this reason, been done on it.

Brito et al. [15] studied the performance of cold chambers by observing the operating parameters, such as enclosure insulation, external temperature, door opening time, etc. It was discovered that thermal insulation of the enclosures was the operating parameter that had the highest impact on the refrigeration that was obtained.

IIis [7] discovered aerogel insulator as one of the thermal insulators that can show great promise in its applications in refrigerators. Aerogel insulation sheets were put to use on the evaporators as well as the different surfaces of the refrigerator as an additional insulator. The results indicated that the application of the aerogel insulation increased the performance of refrigeration.

The performance of a foam-insulated refrigerator, which made use of a liner made from renewable feedstock, was compared with the one that has a liner made from polystyrene [8]. The results obtained in both cases indicated that the performance of a refrigerator can be improved by insulators.

Gökek and Sahim [16] designed a small thermoelectric refrigeration machine, used it to chill water, and examined the performance evaluation of the machine. It was carefully noticed that the refrigerator effectively chilled the water.

A refrigeration system in which glass wool was used as an insulating material was developed by Patil and Pasare [9]. The glass wool was coated with polymethyl methacrylate. The findings from the work indicated that the insulating material coated with polymethyl methacrylate was better than the one without coating.

Maiorino et al. [17] introduced a phase change material in the cabinet of a refrigerator for the change of temperature in the cabinet of the refrigeration system. The outcome of various control settings on the performance of the refrigeration system was investigated, and it was observed that the inclusion of the phase change material improved the refrigeration of the system.

The evaluation of the performance of a refrigeration system for the preservation of fresh maize was developed by Caleb et al. [10]. The materials used for insulation of the refrigerator are mild steel, glass wool, and stainless steel. The refrigerator preserved the fresh maize above the temperature at which maize freezes. It was observed that there were no noticeable changes in the physical appearance and taste of the maize after the refrigerator had preserved it.

The design, fabrication, and test of a solar refrigerator were carried out by Aich and Nayak [11]. Glass wool was used as the insulator in the position that separated the evaporator's wall and the outer chamber of the refrigerator, but the thermocol was used as the insulator in the position that separated the two layers of stainless steel which has been galvanized. The lowest obtainable temperature inside the refrigerator cabinet showed the refrigerator has a reliable operation with the use of glass wool insulation.

Thermoacoustic refrigeration was designed, and its performance was analyzed by

Prashantha et al. [18]. Helium and hydrogen were considered suitable materials or media that can carry away heat to achieve refrigeration. The report of the analysis on the refrigerator showed that the refrigerator has a reliable performance.

Solanki et al. [19] investigated the analysis of a subcooled vapor compression refrigerator to know its performance for commercial chilling of water. The outcome of the performance test inferred that cooling effect could be obtained from the vapor compression refrigerator.

Kamil et al. [20] designed a refrigerating machine that can create a cooling effect by converting acoustic energy to heat energy. The methodology that was adopted to design the machine involved the use of a loudspeaker utilizing a simulation program. The test that was carried out on the machine indicated that it was able to serve the purpose for which it was designed.

Wang et al. [21] investigated the effect that the suction arrangements have on the performance of the compressor that was used on a refrigerator for cooling. The results revealed that the volumetric efficiency of the compressor of the refrigerator could be increased to a ratio of 1.03:1 by a suction delay of 18 degrees. Also, it was discovered that the volumetric efficiency could be increased further by reducing the distance of the suction bearing.

The utilization of the magnetocaloric effect of a magnetic material to achieve refrigeration was examined by Lee [22] on a refrigerator. Concentric Halbach cylinders, which were made up of magnet segments, were used to build the refrigerator. The thermodynamic analysis that was presented on the refrigerator confirmed that refrigeration can be achieved through the magnetic effect.

From the literature presented above, it can be seen that insulation plays a vital role in the effective operation of refrigeration systems. Moreover, the literature review shows that different researchers have carried out various works on refrigeration systems which make use of different insulation materials, such as glass wool, styrofoam, thermocol, polystyrene, polymethyl methacrylate, and aerogel. In the submission of Kirkpatrick [23], there may be a scarcity of these insulators for the production of refrigeration systems. No doubt, this present research has identified a gap in the literature presented above, which is the absence of usage of locally available materials (for example, wood particles) as insulators for refrigeration machines. Therefore, the present work considers it necessary to fill the gap by taking proactive measures to prevent future problems regarding the scarcity of insulators.

In this research, wood particles (a locally available material), which have been converted to particle board, were used as insulation to design and fabricate a refrigeration system. It is important to note that the use of a locally available insulator promotes local content. The refrigerator was used to chill and preserve agricultural products, namely eggs, yohurt, and tomatoes, and the temperatures of the chilled products were compared with their theoretical storage temperatures obtained from the literature.

2. Methodology

This section presents the details of the methodology that was used in the present work. The section is divided into three, namely, the materials used for the work, the fabrication of the refrigerator, and the description of the refrigerator. The flow chart that briefly shows the process of the methodology is shown in **Figure 2**.

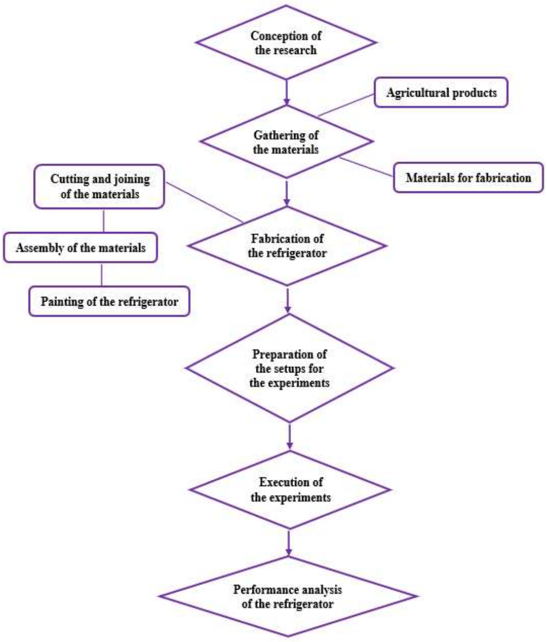

Figure 2. The flow chart of the process of the methodology.

2.1. Materials used for the work

The materials used for the work are agricultural products to be chilled and preserved by the refrigerator, and the materials used for the fabrication of the refrigerator. The agricultural products are eggs, yogurt, and tomato. The products were placed in the interior of the refrigerator. The materials that were used for the fabrication of the refrigerator and their descriptions are shown in **Table 1**.

Table 1. The materials that were used for the fabrication of the refrigerator and their descriptions.

Materials	Descriptions
Mild steel sheet (1 mm thick)	Used for the outer casing of the refrigerator
Particle board (50 mm thick)	A product of wood particles (a locally available material) used as outer insulation of the refrigerator
Polyvinyl chloride PVC (7 mm thick)	Used as the middle insulator of the refrigerator
Aluminum foil (0.5 mm thick)	Used as the inner insulator of the refrigerator
Angle bar (25.4 mm × 25.4 mm, 2 mm thick)	Used to form the framework for the refrigerator
Compressor	A device that moves the refrigerant through the refrigerator
Condenser	A device that takes away heat from the hot refrigerant vapor and condenses into a liquid in saturated state
Evaporator	A device in which the refrigerant circulating inside the refrigerator absorbs the heat energy from the products inside the refrigerator which are then cooled
Expansion valve	A device that lowers the refrigerant's pressure before it enters the evaporator; the pressure drop cools the refrigerant, and then the refrigerant is sprayed into the evaporator
Thermostat	It controls the cooling process by monitoring the temperature and then switching the compressor on and off
Electrical connection	It supplies electric current to the refrigeration system

2.2. Fabrication of the refrigerator

The mild steel sheet and angle bar were cut into the required sizes by a shearing machine. The particle board and the polyvinyl chloride were cut to the required sizes by a circular saw and a hacksaw, respectively. The pieces of the angle bar were joined together by an electric arc welding to form a framework for the refrigerator. The mild steel sheet was fastened to the framework (made from the angle bar) by a power screw machine. The mild steel sheet forms a casing for the refrigerator and the framework makes the casing to be rigid. The particle board was fastened to the framework by a power screw machine. The polyvinyl chloride was installed by laying it on the internal surface of the particle board and then using a hammer tacker to fasten it. The aluminum foil was laid on the polyvinyl chloride with glue and a hammer tacker. **Figure 3** depicts the laying of the walls of the refrigerator.

Figure 3. The laying of the walls of the refrigerator.

The following components were installed on the refrigerator after the insulators had been laid: a compressor, an evaporator, a condenser, an expansion valve, a thermostat, refrigerant lines, and electrical connections (wire and plug). **Figure 4** portrays the installation of these components. After the refrigerator had been fabricated, it was painted white color, as shown in **Figure 5**.

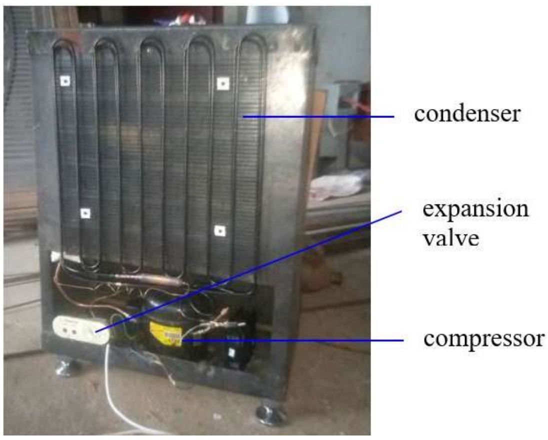

Figure 4. The installation of other components of the refrigerator.

Figure 5. The refrigerator painted white colour.

2.3. Experimental setups

The experimental setups for the egg, yogurt, tomato, and the combined egg, yogurt and tomato are presented in **Figure 6a–d**, respectively. The temperature of the agricultural products was taken using the Type-K digital thermometer before they were put inside the refrigerator. At an interval of half an hour, the temperatures of each of the agricultural products inside the refrigerator were taken and recorded. Thus, the various temperatures at which the egg, yogurt, tomato, and the combined egg, yogurt and tomato were chilled were recorded.

(a) **(b)**

(c) **(d)**

Figure 6. The experimental setups for the temperature drops. **(a)** egg; **(b)** yogurt; **(c)** tomato; **(d)** combined egg, yogurt and tomato.

2.4. Relations for passive and active loads

The two major contributors to refrigeration load are passive and active loads [6].

2.4.1. Passive load

To calculate the heat load from the refrigerator's walls, it is necessary to know the materials chosen for the walls. In addition, the area of the refrigeration chamber should be known. The materials from which the refrigerator's walls were designed are aluminum sheet (internal insulator), polyvinyl chloride (middle insulator), particle board, which is a product of wood particles (outer insulator), and mild steel sheet (outer casing), as presented in **Table 2**.

Table 2. The materials of the walls of the refrigerator.

Material	Thermal conductivity (W/m.K) [24]	Thickness (m)
Aluminum foil	0.00016	0.0005
Polyvinyl chloride	0.15	0.007
Particle board	0.065	0.050
Mild steel sheet	41	0.001

The refrigeration chamber has two compartments. The first one has the inside dimensions of 0.48 m length, 0.32 m breadth, 0.39 m height. The second compartment has the dimensions of 0.48 m length, 0.20 m breadth, 0.27 m height. From **Table 2**, the total thickness of the wall of the refrigerator is 0.117 m (that is, 0.0585 m × 2). Therefore, the outside dimensions of the refrigerator are 0.60 m, 0.56 m, and 0.78 m, respectively. The inside dimensions of the refrigerator are shown in **Figure 7**.

Figure 7. The inside dimensions of the refrigerator.

The inside surface area (A) of the refrigerator is:

[Area of top of the refrigerator] + [Area of one side of the refrigerator] + [Area of top of other side of the refrigerator] + [Area of the front of the refrigerator]. This gives:

$$A = [0.48 \text{ m} \times 0.32 \text{ m}] + [(0.32 \text{ m} \times 0.39 \text{ m}) + (0.20 \text{ m} \times 0.27 \text{ m})]$$
$$+ [(0.32 \text{ m} \times 0.39 \text{ m}) + (0.20 \text{ m} \times 0.27 \text{ m})]$$
$$+ [0.48 \text{ m} \times (0.39 \text{ m} + 0.27 \text{ m})]$$
$$A = 0.1536 \text{ m}^2 + 0.1788 \text{ m}^2 + 0.1788 \text{ m}^2 + 0.3168 \text{ m}^2$$
$$A = 0.828 \text{ m}^2$$

The passive load, which is the heat conveyed into the refrigeration chamber through the refrigerator's walls, can be represented mathematically in Equation (1), as given by Dincer and Kanoglu [2]:

$$Q_P = UA(\Delta T) \tag{1}$$

$$Q_P = \left(\frac{k_s}{t_s} + \frac{k_b}{t_b} + \frac{k_p}{t_p} + \frac{k_l}{t_l}\right) \times A \times (T_a - T_i) \tag{2}$$

where k_s, k_b, k_s, k_p, and k_l are the thermal conductivity of the mild steel, particle board, polyvinyl chloride and, aluminum foil; t_s, t_b, t_s, t_p, t_l are the thickness of the mild steel, particle board, polyvinyl chloride and aluminum sheet; T_o is ambient temperature (27 °C); T_i is average preservation temperature for the combination of the agricultural products used in this work.

2.4.2. Active load

The heat load from the agricultural products inside the refrigerator is given in Equation (3), published by Dincer and Kanoglu [2]:

$$Q_m = mc_p\Delta T = mc_p(T_o - T_i) \tag{3}$$

where Q_m is the heat load from the agricultural products, m is the mass of the products, c_p is the specific heat capacity of the products T_o is the temperature of the products inside the refrigerator at the start of the experiment (27 °C), and T_i is average preservation temperature for the combination of the three products considered in this work.

3. Results and discussions

3.1. Temperature drop of egg

The temperature of the eggs before they were put inside the refrigerator was 27 °C. As can be seen in the outcomes of the experiment shown in **Figure 8**, the temperature of the eggs on the inside of the refrigerator at the start of the experiment is 27 °C. At 30, 60, and 90 min thereafter, the temperature of the eggs drops to 25 °C, 21 °C, and 18 °C, respectively. The temperature is 16 °C, 14 °C, 12 °C, and 11 °C at intervals of 120, 150, 180, and 210 min, respectively. The preservation temperature of the egg, according to the report of the Department of Plant Sciences at the University of California [25], is 18 °C to 21 °C. This is higher than the temperature of 11 °C which was recorded in the present experiment after 210 min. It, therefore, indicates that the refrigerator can chill and preserve eggs. The minimum theoretical preservation temperature, the maximum theoretical preservation temperature, and the experimental preservation temperature (obtained in the present work) of the egg are portrayed in **Figure 9**.

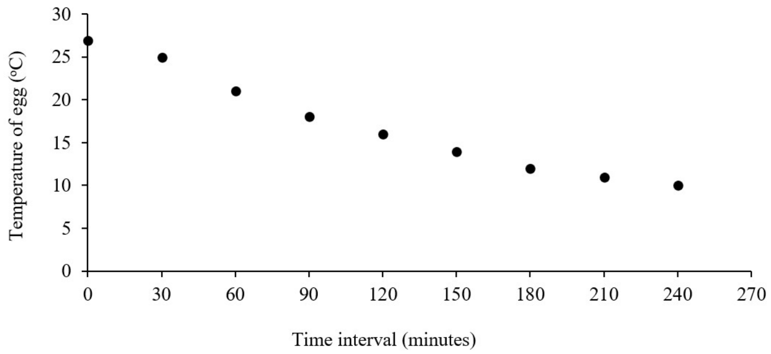

Figure 8. The temperature of the egg.

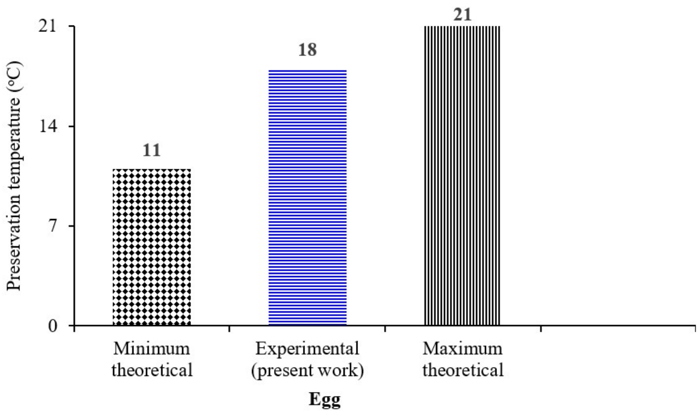

Figure 9. The theoretical and experimental temperatures of the egg.

3.2. Temperature drop of yogurt

The results for the temperature of the yogurt, as shown in **Figure 10**, reveal that a temperature of 27 °C was recorded for the yogurt before they were put inside the refrigerator, which was the temperature of the yogurt inside the refrigerator at the start of the experiment. The temperature drops at intervals of 30, 60, 90, and 120 min to 25 °C, 22 °C, 20 °C, and 18 °C, respectively. The temperature is 17 °C, 15 °C, and 13 °C at intervals of 150, 180, and 210 min, respectively. The temperature drops at intervals of 240 min and 270 min to 10 °C and 7 °C, respectively. The temperature of 7 °C is approximately equal to 5 °C, which is the theoretical preservation temperature of yogurt [25]. This is an indication that the refrigerator can chill and preserve yogurt. The theoretical preservation temperature and the experimental preservation temperature (obtained in the present work) of the yogurt are depicted in **Figure 11**.

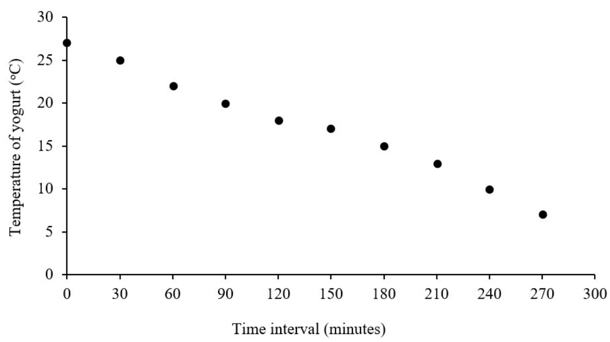

Figure 10. The temperature of the yogurt.

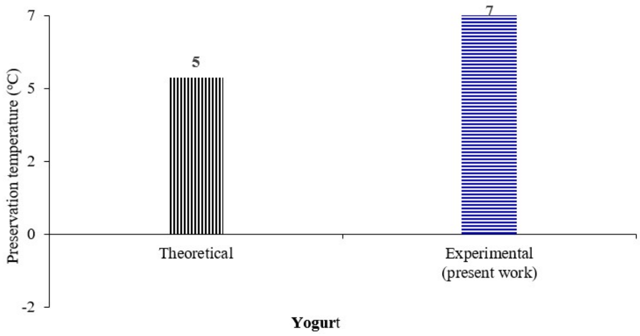

Figure 11. The theoretical and experimental temperatures of the yoghurt.

3.3. Temperature drop of tomato

As can be in the results of the experiment shown in **Figure 12**, the temperature of the tomato inside the refrigerator at the start of the experiment is 27 °C. At 30 min and 60 min after that, the temperature of the tomato drops to 21 °C and 16 °C, respectively. The temperature is 13 °C, 10 °C, and 8 °C at intervals of 90, 120, and 150 min, respectively. The theoretical preservation temperature of tomato is 7 °C to 10 °C [25], whereas the experimental preservation temperature is 8 °C. Therefore, tomato can be chilled and preserved by the refrigerator. The minimum theoretical preservation temperature, the maximum theoretical preservation temperature, and the experimental preservation temperature (obtained in the present work) of the tomato are displayed in **Figure 13**.

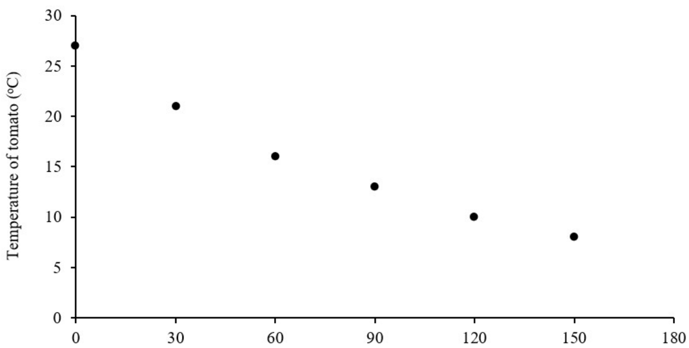

Figure 12. The temperature of the tomato.

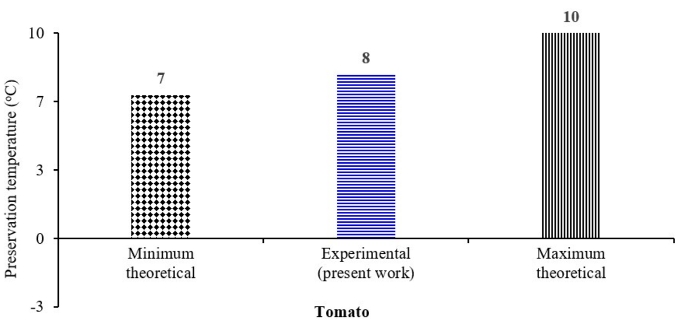

Figure 13. The theoretical and experimental temperatures of the tomato.

3.4. Temperature of the combined egg, yogurt and tomato

The temperature of the combined agricultural product before they were placed inside the refrigerator was 27 °C. The results of the experiment for the temperature of the combined agricultural product are shown in **Figure 14**. A temperature of 27 °C was recorded for the combined product before they were put inside the refrigerator. The temperature of the combined product inside the refrigerator at the start of the experiment is 27 °C. The temperature drops at intervals of 30, 60, 90, 120, and 150 min to 23 °C, 18 °C, 17 °C, 16 °C, and 15 °C, respectively. The temperature is 14 °C, 12 °C, 11 °C, and 10 °C at intervals of 180, 210, 240, and 270 min, respectively. This minimum temperature of 10 °C, which was recorded for the combined egg, yogurt and tomato at the interval of 270 min, is 1 °C, 3 °C, and 2 °C deviated from the temperature at which the refrigerator can chill and preserve the egg, yogurt and tomato, respectively. It, therefore, means that the refrigerator can chill and preserve the combined eggs, yogurt and tomatoes at the temperature of 10 °C.

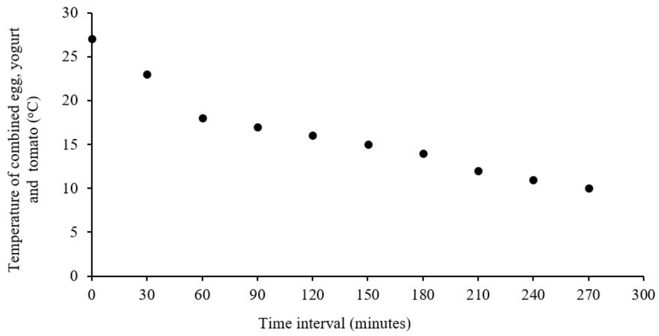

Figure 14. The temperature of the combined egg, yogurt and tomato.

3.5. Passive and active loads

It is necessary to consider the passive and active loads, which are the major contributor loads on the refrigerator. The passive load is the heat load from the refrigerator's walls, whereas the heat load from the agricultural products inside the refrigerator is the active load.

From the previous section, the preservation temperature for the combined egg, yogurt, and tomato is 10 °C. Substituting the appropriate values into Equation (2) gives the passive load (Q_P):

$$Q_P = \left(\frac{41}{0.001} + \frac{0.065}{0.050} + \frac{0.15}{0.007} + \frac{0.00016}{0.0005}\right)\frac{W/m.K}{m} \times 0.828\, m^2 \times (27-10)K$$

$$Q_P = 577.44\, kW.$$

As given in Equation (3) above, the expression for the active load (Q_m) is:

$$Q_m = mc_p\Delta T = mc_p(T_o - T_i)$$

The specific heat capacity of the combined egg, yogurt, and tomato ($C_{p,c}$) [26] is

$$c_{p,c} = x_1 c_{p,1} + x_2 c_{p,2} + \cdots + x_n c_{p,n} \quad (4)$$

where x is the mass fraction of the components in the combined product, and subscripts 1, 2, …, n are the components.

The mass and specific heat capacity of the agricultural products are provided in **Table 3**.

Table 3. The mass and specific heat capacity of the agricultural products.

Agricultural products	**Mass (kg)**	**Specific heat capacity (J/kg.K) [25]**
Egg	1.53	888
Yogurt	2.2	3520
Tomato	0.68	3517.4

Applying Equation (4) in conjunction with the mass and specific heat capacity in **Table 3** gives the specific heat capacity of the combined product to be

$$c_{p,c} = \frac{[(1.53 \times 888) + (2.21 \times 3{,}520) + (0.68 \times 3{,}517.4)]\ kg.\frac{J}{kg.K}}{4.42\ kg}$$

$$c_{p,c} = 2{,}608.52\ J/kg.K$$

Substituting the appropriate values into Equation (3) gives the active load (Q_m):

$$Q_m = 4.42\ kg \times 2608.52\ J/kg.K \times (27 - 10)K = 196.00\ kJ$$

The average time for the combination of the combined product to reach the preservation temperature is 270 min, as can be seen in the above calculations. That is, the active load is $196\ \text{kJ}/270\ \text{mins} = 0.0121\ \text{kW}$.

4. Conclusions

As refrigeration is one of the means of preservation of agricultural products, and in order to explore the potential of locally available materials to achieve the refrigeration, a vapor compression refrigeration system was designed and fabricated to chill and preserve agricultural products, namely eggs, yogurt, and tomatoes.

The refrigerator makes use of wood particles (a locally available material), which have been converted to particle board, as one of its insulators. Different experiments were carried out on the refrigerator to find out the various temperatures at which the agricultural products became chilled and preserve the products.

In the cases of egg and tomato, the experimental preservation temperatures of 11 °C and 8 °C, respectively, obtained in the present work are lower than the theoretical preservation temperature of 18 °C to 21 °C and 7 °C to 10 °C, respectively, obtainable in the literature. In the case of yogurt, the experimental preservation temperature of 7 °C obtained in the present work is approximately the same as the theoretical preservation temperature of 5 °C obtainable in the literature. The results give strong indications that the refrigerator can effectively chill and preserve agricultural products.

The performance of the refrigerator further indicated that a locally available material, which is wood particles that have been converted to particle board, can be reliably used as an insulator for the achievement of refrigeration by a refrigerator, making the wood particles an attractive alternative to insulation materials. This will promote local content, and make it easy to take a proactive measure in preventing future problems regarding scarcity of insulators that are required for refrigeration.

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Conflict of interest: The authors declare no conflict of interest.

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