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Research Article

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Development of A Solar-Powered Refrigeration System for The Preservation of Fruits and Vegetables

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Abstract: The solar-powered refrigeration system is a portable unit designed for food preservation in off-grid locations. It operates independently on solar energy through a 250 W photovoltaic system, converting solar radiation into electrical energy. The system incorporates a smart charge controller, a 12 V lead-acid battery for reliable and uninterrupted power supply, and a 1.5 kVA inverter that powers the refrigeration system. The refrigeration system consists of a thermally insulated compartment and a compressor, designed for a total capacity of 1.3959 kW, a condenser, a capillary tube, and an evaporator, engineered for a cooling load of 0.5816 kW at 7°C. A data logger was used to monitor temperature and humidity levels in both the cabinet and the surrounding environment, while a thermostat regulated the cabinet temperature to maintain optimal freshness. The refrigeration system was evaluated under no-load conditions for three days and on-load for thirty days with tomatoes and peppers, running for ten hours daily. The system achieved a COP of 6.001 at an internal temperature of 7°C against an ambient temperature of 33.7°C, demonstrating its efficiency in food preservation. The qualitative analysis of the refrigerated produce after thirty days, comparing their appearance and texture with freshly harvested samples and those stored at room temperature, confirmed the system's quality. Organoleptic evaluation revealed that the products maintained good texture and taste.

Keywords: Solar-powered refrigeration, food preservation, photovoltaic system, temperature, humidity, tomatoes and peppers

1. Introduction

Utilizing low temperatures to completely stop or significantly slow down the activity of spoiling agents is a key component of the refrigeration process used to preserve perishable food products. The type of product being stored and the duration of its storage determine the necessary low temperature for effective preservation. Although, Refrigeration is very popular but it has been observed that several fruits and vegetables cannot be stored in the domestic refrigerator for a long period as they are susceptible to chilling injury, in Nigeria and other countries around the world, vegetables and fruits are important food items that are widely consumed because they form an essential part of a balanced diet (Mogaji, 2019a). In order to protect quality and extend shelf life of fresh agricultural produce such as fruits and vegetables, they should always be cooled as soon as possible after harvest. This is because once harvested, produce gains heat through respiration and conduction from the surrounding environment. Cooling involves heat transfer from produce to a cooling medium such as a source of refrigeration. The heat transfers processes involved during refrigeration process include conduction, convection, radiation and evaporation. Fresh fruits and vegetables are living tissues separated from the parent plant, which supplied them with water via transpiration. Fruits and vegetables grown by subsistence farmers are stable foods for millions of people around the world, especially in Africa. Fruits and vegetables have been in the diet of Nigerians for centuries and have gradually become a more important horticultural crop (Mogaji, 2019b).

The continued increase in world population and rapid urbanization has resulted in a gradual increase in global energy demands. Developed countries use fossil fuels like coal, oil and natural gas for various domestic and industrial purposes (Chakraborty, 2021). The rapidly growing world energy consumption has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming and climate change (Mogaji et al., 2020). The conventional cooling system consumes more electrical energy for cooling (Harby and Fahad, 2019). A compressor is the most power-consuming component in a refrigeration system, and energy scarcity in the form of electricity has become a grave challenge in today's world. Replacing traditional energy sources for a compressor with solar-powered clean energy could be an efficient alternative to significantly reduce energy consumption (Dhawan et al., 2023).

2. Research Methodology

Materials and Equipment

The system was constructed using various materials, including a 1 mm thick mild steel sheet, a 1 mm diameter metal rod, a galvanized aluminum sheet, a 0.4 m iron bar, fasteners such as screw bolts, bolts and nuts, brazing rod and powder, electrodes, fiberglass for insulation, and white emulsion paint. Key refrigeration components included an evaporator, rubber hose, plastic container, electric motor, refrigerants (R22 for system charging and R134a for mechanical cooling), a 0.41 TR, 1/8 hp compressor, wire-and-tube air-cooled condenser, drier, and accumulator. The system was powered by photovoltaic (PV) solar panels, an inverter, a battery, and a charge regulator to manage electricity flow, preventing overcharging and excessive discharge, ensuring reliable and efficient operation. The components of the solar system are shown in Figure 1a-d.

Methods

Determination of size of the refrigerating system

The total surface area of the refrigerated space is given by equation (1)

$$A_s = 2(H \times L) + 2(H \times B) + 2(L \times B) \quad (1)$$

The volume of the refrigeration system is given by equation (2)

$$A_s = 2(H \times L) + 2(H \times B) + 2(L \times B) \quad (2)$$

The volume of compressor and plastic container space is given by equation (3)

$$V_O = L_O \times B_O \times H_O \quad (3)$$

The volume of the refrigerated space is given by equation (4)

$$V_R = V_T \times V_O \quad (4)$$

Where: H is the height of the refrigerated space; B is the breadth of the refrigerated space; L is the length of the refrigerated space; t is the thickness of walls of the refrigerated space; H_O is the height of plastic container space; B_O is the breadth of the plastic container space and L_O is the length of the plastic container space.

Determination of cooling load capacity

The heat sources considered in the design of this refrigeration system are:

Figure 1: Solar PV Panel (a), Charge Controller (b), Battery (c), and Battery (d).

(i) Transmission Load (TL)

The transmission load was calculated using Equation (5) as provided by Dossat (1979).

$$Q_{trans} = A_S U \Delta T \quad (5)$$

Where: Q_{trans} is the rate of heat transfer (W); A_S is the outside surface area of the walls (m^2); U is the overall heat transfer coefficient for the materials used (W/m^2K); ΔT is the temperature different across the walls (K), K_{in} is the thermal conductivity of the insulating Therefore,

$$U = \frac{K_{in}}{x} \quad (6)$$

$K_{in} = 0.036\ W/mK$

$x = 0.10\ m$

material (fiber glass) and x is the thickness of the refrigerator walls = 0.1 m.

(ii) Product Load

(a) The heat generated by the product as a result of respiration can be determined using Equation (7) (Dossat, 1979).

$$Q_{resp} = \sum M_{TP} q_{rp} \quad (7)$$

(b) Heat removed from the products was calculated using equation (8) Dossat, (1979)

$$Q_P = \frac{M_{TP} C_P \Delta T}{\text{Desired cooling time}} \quad (8)$$

The total products load (Q_{tP}) would be equal to the total amount of heat absorbed.

$$Q_{tp} = Q_{resp} + Q_p \quad (9)$$

(iii) Infiltration load

The infiltration load is determined using Equation (10) (ASHRAE, 2001).

$$Q_{infilt} = I_{fR} \times \text{Enthalpy change} \quad (10)$$

Where: Q_{infilt} is the heat gain which is associated with the air entering the refrigerated space per second (kW); I_{fR} is the infiltration rate, that is, the volume of air entering the refrigerated space per second (L/s) (litre per second) and Enthalpy change is the heat gain per unit volume (kJ/L).

(iv) Light load

The value was determined using equation (11) as specified by ASHRAE (2001).

$$Q_{LL} = \frac{\text{kWh}}{\text{Time Taken}} \quad (11)$$

Where: Q_{LL} is the light load per second (kW); kWh is the electrical energy consumed by an appliance when the power of one kilowatt (kW) is used by the appliance for one hour; Time taken, is the time used for a whole day (24 hours).

(v) Total cooling load

This was the summation of all the loads from various sources as calculated using equation (12).

$$Q_{tCL} = Q_{LL} + Q_{infilt} + Q_{Trans} + Q_p \quad (12)$$

Required equipment capacity

This refers to the capacity at which the equipment operates most efficiently, expressed in kilowatts (kW) using equation (13) Dossat (1979):

$$REC = \frac{Total\ cooling\ load \times 24\ hours}{The\ Operating\ time} \quad (13)$$

Compressor analysis

To determine the compressor size (CS)

REC = $1.3959096624\ kW$ per 10 hours and $1Hp = 0.746\ kW$

$$x = \frac{1.3959096624\ kW}{0.746} = 1.8712$$

Where: REC is the Required Equipment Capacity, HP is one horse power = 0.746 kW; x is the number of horse power and the desired running time per day is 10 hours. Then, the compressor size (CS) was determined using equation (14) Dossat (1979):

$$CS = \frac{x}{10} \quad (14)$$

$$CS = \frac{1.8712}{10} = 0.18712 \approx \frac{1}{8} HP\ Compressor\ size$$

Refrigerating capacity of the compressor

The following steps were taken to determine the refrigerating capacity of the compressor to be used in this refrigeration system as follows:

i. The desire to refrigerate the perishable products at the temperature of 7 ºC to ensure that the micro-organisms would not have the tendency of destroying the products in order to retain their values and freshness.

The properties of Refrigerant 134a at various temperatures were obtained from ASHRAE handbook, ASHRAE (2001).

ii. The refrigerating effect (RE) was calculated using equation (15)

$$RE = h_2 - h_1 \tag{15}$$

The mass flow rate (ṁ) of the refrigerant was calculated using equation (16) Dossat (1979):

$$\dot{m} = \frac{REC}{RE} \tag{16}$$

Where: ṁ is the mass flow rate; REC is the Required Equipment Capacity

iii. The compressor power required was calculated using equation (17)

$$CPR = \dot{m}\,(RE) \tag{17}$$

i. The refrigerating capacity of the compressor (RCC) was calculated using equation (18) ASHRAE (2001)

$$RCC = \frac{CPR}{3.51} \tag{18}$$

Work done by the compressor

The workdone by the compressor was calculated from the values of the enthalpy of the vapour refrigerant at 10 ºC and 30 ºC which were at the suction tube and discharged piping tube respectively. The enthalpy at 10 ºC and 30 ºC were read from ASHRAE (2001) refrigerant property table, as $h_{10} = h_g = 256.16\ kJ/kg$ and $h_{30} = h_g = 266.66\ kJ/kg$, respectively.

Workdone (W) was calculated using equation (19)

$$W = h_{30} - h_{10} \tag{19}$$

Coefficient of performance

The coefficient of performance (COP) was calculated using equation (20) Dossat (1979)

$$COP = \frac{RE}{W} \tag{20}$$

Design of the photo-voltaic system

The Photo-Voltaic system's design was done by following the steps highlighted.

i. Refrigerator energy requirement in watt- hours (Wh)/day

The refrigeration system is designed to run for 10 hours daily. Consequently, for a refrigerator rated at 100 watts, the energy consumption was determined using equation (21).

$$\text{Daily Energy Use}\left(\frac{\text{Wh}}{\text{day}}\right) = \text{Power Rating (W)} \times \text{Daily Operating Time}\left(\frac{\text{hours}}{\text{day}}\right) \tag{21}$$

ii. Total energy to be delivered by the PV panel per day

Refrigerator load = 1000 Wh/day

Considering system inefficiencies, compensation for losses (20% of load) was assumed = 200Wh/day

$20\%\ of\ 1000\ Wh/day$

iii. Sunlight availability

The availability of sunlight in Akure, Nigeria (Latitude 7°15′00″ N, Longitude 5°11′24″ E) was considered to be 5.21 hours per day (Melodi and Famakin, 2011).

iv. Determination of PV array size needed

The PV array size was calculated using equation (22)

$$PV\ Array\ Size = \frac{Total\ Energy\ Requirement\ (Wh/day)}{Peak\ Sun\ Hours\ (h/day)} \tag{22}$$

v. Size of battery bank

The Ampere-hour per day (Ah) required from the battery is calculated as follows:

Total Refrigerator Load = 1000 Wh/day

Battery Voltage = 12 V

Ah needed per day = (1000 / 12) = 83.33 Ah/day
A 12 V, 500 Ah deep cycle battery was chosen, with a depth of discharge of 20%, which equates to 100 Ah.

vi. Minimum required battery capacity

The daily required ampere-hours (Ah) are equal to 100 Ah. It is anticipated that the battery will run for the two allotted days of autonomy. Thus, the required battery size is (100 x 2) = 200 Ah at 12 V. A 12 V battery or two 6 V batteries connected in series can be used to reach this battery capacity.

vii. Charging regulator

To optimize the charge drawn from the solar module and protect the system from overvoltage or undervoltage, an 8-amp, low voltage cut-off, Pulse Width Modulation (PWM) solar charge controller was used.

viii. An automatic inverter that converts 12 Volt DC to 220 Volt 50Hz AC electricity, with a continuous output of 400 watts and a peak power of 800 watts, was utilized. It has 85% efficiency. Figure 2 shows the circuit diagram.

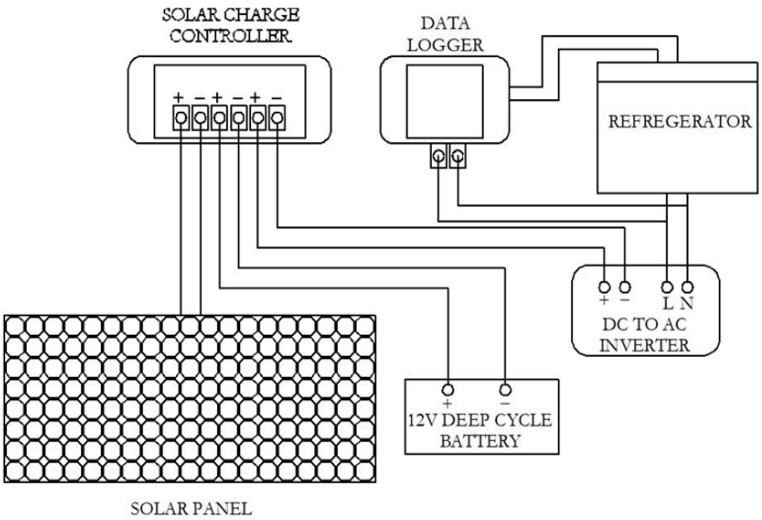

Figure 2: Circuit Diagram

Assembly layout

The assembly layout of the smart solar-powered refrigeration system is presented in Figure 3 a-e, illustrating the arrangement and positioning of each component utilized in the system.

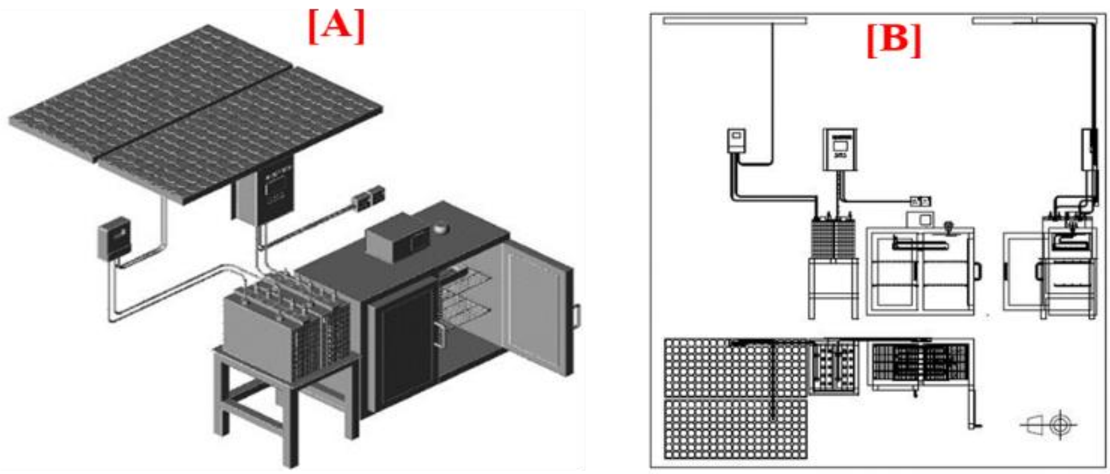

Figure 2: Isometric view of the design (a), Plan view of the design (b)

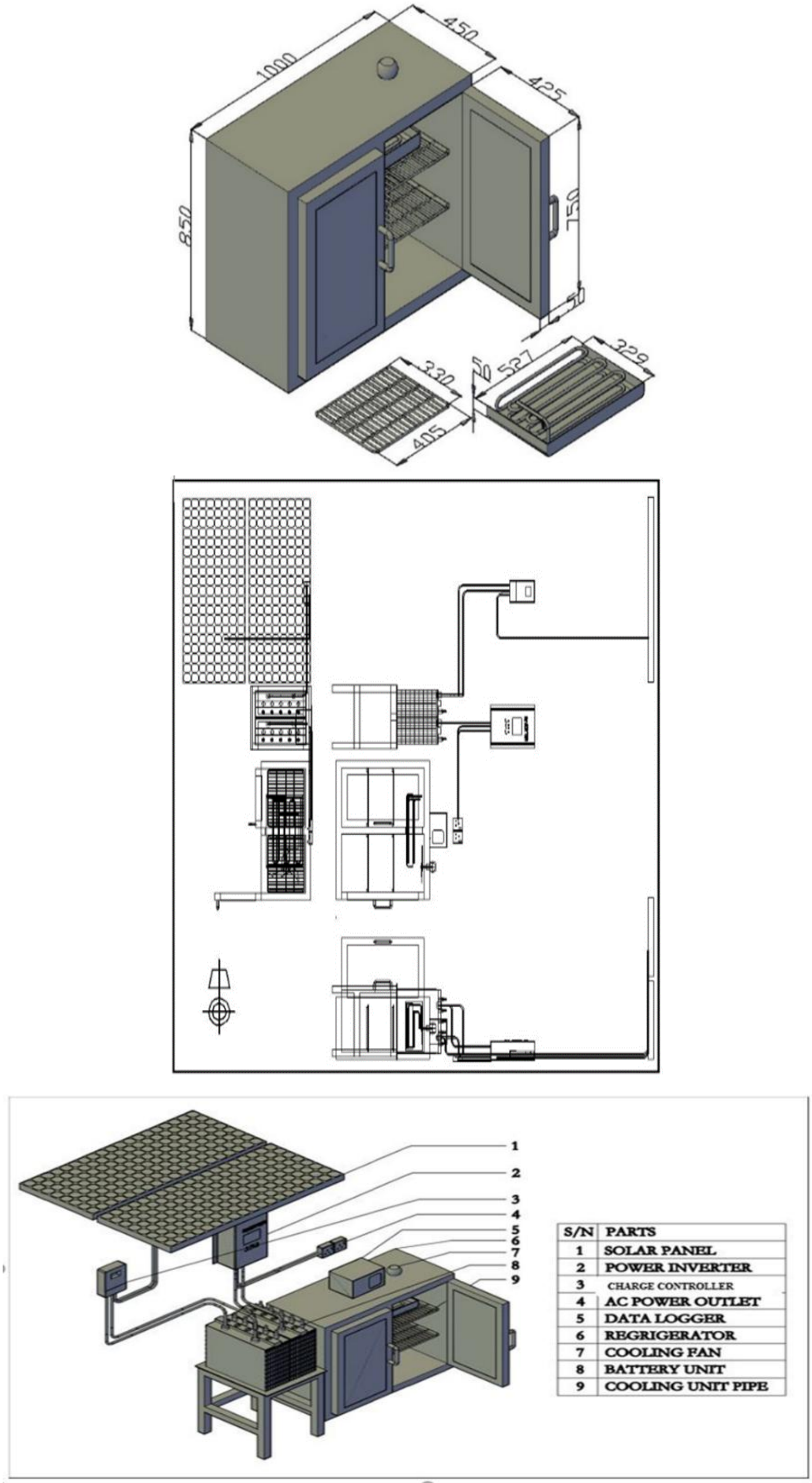

Figure 2: Front view of the cabinet design (c), Back view of the design (d) and Complete view of the design (e).

3. Results and Discussion

Test Procedure

To evaluate the performance of the solar-powered refrigeration system, a series of experimental tests were conducted using perishable food items. The system was tested under both on-load and no-load conditions, with key parameters recorded to analyze its efficiency.

Experimental Setup

(a) Perishable food items, specifically tomatoes and peppers, were used as test loads.

(b) The system was equipped with a data logger to continuously record critical performance parameters.

Data Collection

Measurements were taken at 30-minute intervals for 10 hours daily over a 30-day period to assess system performance. The following parameters were monitored:

(a) Environmental Conditions: Ambient temperature and relative humidity in both load and no-load conditions.

(b) Internal Conditions: Temperature and relative humidity in each compartment of the refrigerator.

(c) Refrigeration System Components: Evaporator, condenser, and compressor temperatures.

(d) Solar Power System Performance: Solar panel voltage and current, battery voltage, and state of charge.

Performance Analysis

The recorded parameters and operational data were used to compute key performance indicators, including: Refrigerating effect, Compression work, Coefficient of performance (COP), Mass flow rate, Power consumption, and Refrigeration capacity. These measurements provided insights into the system's operational efficiency and its ability to preserve perishable food items under real-world conditions. Obtained results for both on-load and load conditions are presented in Table 3 - 8.

Results

The result of the testing of solar-powered refrigerator is presented in Table 3-7.

(i) On No Load

Table 3: Cabinet and Ambient Readings on No – Load Condition

S/N	Time (mins)	Ambient Temperature (℃)	Ambient Relative Humidity (%)	Upper Cabinet Temperature (℃)	Upper Cabinet Relative Humidity (%)	Middle Cabinet Temperature (℃)	Middle Cabinet Relative Humidity (%)
1	0	33.70	50.00	27.30	60.07	27.40	59.92
2	30	33.70	50.00	27.20	60.23	27.10	60.39
3	60	33.70	50.00	27.00	60.55	26.99	60.56
4	90	33.70	50.00	25.80	62.43	25.60	62.75
5	120	33.70	50.00	22.89	67.01	23.78	65.61
6	150	33.70	50.00	20.01	71.55	20.04	71.50
7	180	33.70	50.00	17.01	76.27	17.56	75.40
8	210	32.80	51.42	13.42	81.92	14.01	80.99
9	240	32.80	51.42	12.12	83.96	12.47	83.41
10	270	33.70	50.00	10.59	86.37	11.28	85.28
11	300	32.80	51.42	9.99	87.31	9.42	88.21
12	330	33.20	50.79	9.01	88.86	8.98	88.90
13	360	33.20	50.79	8.45	89.74	8.54	89.60
14	390	33.70	50.00	8.00	90.45	8.05	90.37
15	420	33.20	50.79	7.51	91.22	7.64	91.01
16	450	33.70	50.00	7.20	91.71	7.34	91.48
17	480	32.80	51.42	7.11	91.85	7.18	91.74
18	510	33.20	50.79	7.07	91.91	7.06	91.93
19	540	37.60	43.87	7.04	91.96	7.03	91.97
20	570	33.20	50.79	7.02	91.99	7.01	92.00

Table 4: Evaporator, Suction, Discharge and Condenser Temperatures Obtained On No - Load Condition

S/N	Times (mins)	Evaporator Temperature (℃)	Suction Temperature (℃)	Discharge Temperature (℃)	Condenser Temperature (℃)
1	0	30.24	35.42	34.40	72.24
2	30	12.63	26.02	52.60	79.15
3	60	11.74	27.32	57.50	82.14
4	90	11.09	28.32	60.70	84.37
5	120	10.19	28.32	60.80	86.56
6	150	10.14	29.32	61.80	87.15
7	180	10.14	29.32	61.80	88.14
8	210	10.09	29.32	62.80	89.15
9	240	9.89	30.42	61.50	91.24
10	270	9.20	28.32	61.50	91.44
11	300	9.20	28.32	61.40	91.84
12	330	8.69	28.42	60.50	92.34
13	360	8.49	29.42	64.30	92.14
14	390	8.39	29.42	64.30	93.14
15	420	8.39	29.42	64.40	94.14
16	450	8.39	29.42	64.30	95.38
17	480	8.49	29.42	64.30	95.57
18	510	8.49	29.42	64.30	95.74
19	540	8.24	27.92	63.30	95.97
20	570	8.24	27.92	63.30	96.16

Table 5: Calculated Parameters with Corresponding Results on No – Load Condition

S/N	Refrigerating Effect (kJ/kg)	Mass Flow Rate (kg/s)	Compressor Work(kJ/kg)	Compressor Power Required (kW)	Coefficient of performance
1	-	-	-	-	-
2	76.12	0.0183	11.49	0.21	6.62
3	76.46	0.0183	12.39	0.23	6.17
4	78.24	0.0178	12.79	0.23	6.12
5	75.27	0.0185	12.81	0.24	5.88
6	75.71	0.0184	12.55	0.23	6.03
7	75.71	0.0184	12.55	0.23	6.03
8	75.67	0.0184	12.79	0.24	5.92
9	76.31	0.0183	11.95	0.22	6.39
10	76.42	0.0183	12.97	0.24	5.89
11	76.42	0.0183	12.95	0.24	5.90
12	74.1	0.0188	12.69	0.24	5.84
13	74.43	0.0188	13.09	0.25	5.69
14	74.35	0.0188	13.09	0.25	5.68
15	74.35	0.0188	13.12	0.25	5.67
16	74.35	0.0188	13.09	0.25	5.67
17	74.43	0.0188	13.09	0.25	5.69
18	74.43	0.0188	13.09	0.25	5.69
19	73.48	0.0190	13.60	0.26	5.40
20	73.48	0.0190	13.60	0.26	5.40

(ii) On Load

Table 6: Cabinet and Ambient Readings on Load Condition

S/N	Time (mins)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Upper Cabinet Temperature (°C)	Upper Cabinet Relative Humidity (%)	Middle Cabinet Temperature (°C)	Middle Cabinet Relative Humidity (%)
1	0	33.70	50.00	27.40	59.92	27.30	60.07
2	30	33.20	50.79	27.20	60.23	27.10	60.39
3	60	32.40	52.05	26.00	62.12	25.90	62.28
4	90	32.20	52.36	23.50	66.05	23.90	65.42
5	120	32.20	52.36	23.50	66.05	23.92	65.39
6	150	32.20	52.36	23.50	66.05	23.90	65.42
7	180	33.20	50.79	23.50	66.05	22.55	67.55
8	210	33.70	50.00	23.00	66.84	22.10	68.26
9	240	33.70	50.00	22.50	67.63	21.90	68.57
10	270	32.80	51.42	21.50	69.20	21.50.	69.20
11	300	32.90	51.26	19.20	72.82	18.45	74.00
12	330	33.20	50.79	17.50	75.50	17.00	76.28
13	360	34.10	49.37	16.00	77.86	16.50	77.07
14	390	34.10	49.37	13.50	81.79	12.90	82.74
15	420	34.10	49.37	10.90	85.88	11.00	85.73
16	450	34.30	49.06	10.90	85.88	10.85	85.96
17	480	32.80	51.42	10.90	85.88	10.80	86.04
18	510	32.80	51.42	9.50	88.09	9.05	88.79
19	540	35.60	47.01	9.00	88.87	9.02	88.84
20	570	32.80	51.42	8.50	89.66	8.75	89.27

Table 7: Evaporator, Suction, Discharge and Condenser Temperatures Obtained on Load Condition

S/N	Times (mins)	Evaporator Temperature (°C)	Suction Temperature (°C)	Discharge Temperature (°C)	Condenser Temperature (°C)
1	0	21.03	23.28	45.75	43.62
2	30	14.83	23.68	55.45	48.62
3	60	14.03	25.68	59.75	49.62
4	90	13.73	26.48	63.11	50.02
5	120	13.48	27.08	64.05	50.62
6	150	13.03	27.08	64.35	51.62
7	180	13.28	27.08	64.55	52.12
8	210	13.23	26.48	66.05	52.42
9	240	12.63	26.48	64.85	52.62
10	270	12.53	26.48	64.75	52.72
11	300	12.43	26.58	65.05	52.82
12	330	12.03	26.48	63.45	53.02
13	360	11.28	25.38	61.35	53.32
14	390	10.68	25.38	61.35	53.62
15	420	10.03	25.38	61.25	53.72
16	450	9.83	23.88	61.05	53.92
17	480	9.43	23.88	52.75	54.22
18	510	9.28	24.68	54.55	54.92
19	540	9.13	24.88	55.55	55.22

20	570	8.98	24.88	55.95	55.42

Table 8: Calculated Parameters with Corresponding Results on Load Condition

S/N	Refrigerating Effect (kJ/kg)	Mass Flow Rate (kg/s)	Compressor Work (kJ/kg)	Compressor Power Required (kW)	Coefficient of Performance
1	-	-	-	-	-
2	76.79	0.0182	13.61	0.248	5.64
3	77.13	0.0181	13.87	0.251	5.56
4	77.27	0.0181	14.27	0.258	5.41
5	77.37	0.0180	14.20	0.256	5.45
6	76.99	0.0181	14.27	0.259	5.40
7	77.20	0.0181	14.31	0.259	5.40
8	76.86	0.0182	14.89	0.270	5.16
9	76.36	0.0183	14.68	0.268	5.20
10	76.27	0.0183	14.66	0.268	5.20
11	76.19	0.0183	14.73	0.270	5.17
12	75.86	0.0184	14.35	0.264	5.29
13	74.69	0.0187	14.41	0.269	5.18
14	74.20	0.0188	14.41	0.271	5.15
15	73.66	0.0190	14.39	0.272	5.12
16	72.74	0.0192	15.10	0.290	4.82
17	72.41	0.0193	12.62	0.243	5.74
18	72.70	0.0192	12.80	0.246	5.68
19	72.68	0.0192	13.04	0.250	5.58
20	72.55	0.0192	13.17	0.253	5.51

Discussion

Figure 12 shows that as the evaporator temperature decreases, the compressor power requirement also decreases, while the compression work increases. The initial drop in power consumption occurs because more energy is needed to initiate the compression process. However, once the system stabilizes, the power requirement gradually declines as the evaporator temperature continues to decrease. On the other hand, compression work increases with decreasing evaporator temperature due to the rise in vapor refrigerant, which leads to an increase in evaporating pressure. These findings align with the study, conducted by Akinola et al. (2008). As depicted in Figure 13, a rise in condensing temperature results in an increase in compression work while simultaneously reducing the compressor's power requirement. The compressor power requirement, determined by the product of the mass flow rate and the work of compression, gradually declines as the mass flow rate decreases. This reduction occurs due to the increasing specific volume of the refrigerant at the compressor inlet. These findings are consistent with those reported by Akinola et al. (2008). Organoleptic evaluation revealed that the preserved products maintained desirable attributes such as appearance, smell, taste, and texture. However, as consumer and processor assessments of these qualities are subjective, slight variations were observed regarding their perceived freshness. Overall, the preserved products compared favorably with fresh ones.

4. Conclusion

A solar-powered vapor compression refrigeration system with a capacity of 0.41 TR and a coefficient of performance of 6.0 was successfully designed, constructed, and evaluated. The system utilized solar energy to effectively operate a conventional refrigerator, significantly reducing the spoilage and waste of perishable food items. Although the initial production cost was high due to its single-unit design, the operating costs were substantially lower in the long run, thanks to its efficient power consumption. This underscores the potential of solar energy as a reliable alternative power source, especially for small-scale, stand-alone applications in rural areas where electricity is unreliable or unavailable. The system was tested for preserving fresh tomatoes and peppers, successfully keeping tomatoes fresh for 30 days with only 8% spoilage and peppers for the same duration without any spoilage. Physical evaluations of the appearance, texture, and color of the refrigerated produce compared to samples stored at room temperature for 30 days showed that the refrigerated samples retained their quality, texture, odor, and appearance, similar to those freshly harvested from the farm.

Recommendations:

Based on the findings of this project and the conclusions drawn from the solar-powered refrigeration system, the following recommendations are proposed:

(i) Solar-powered refrigeration systems should be adopted to reduce environmental impact while promoting sustainable energy use.

(ii) These systems are particularly recommended for areas with limited or unreliable electricity supply where refrigeration is essential.

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