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Optimization of Low-Voltage DC Compressor Performance in Solar-Powered Refrigeration Systems for Off-Grid Applications

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Abstract— **This innovative solar-powered refrigerator, adapted from a conventional AC refrigerator, offers a sustainable and eco-friendly solution for preserving food in off-grid environments. Powered by solar panels, it operates on a low-voltage DC system, ensuring efficient energy utilization. With a 120-liter capacity and R134a refrigerant, the refrigerator can maintain optimal temperatures even during periods of low sunlight. Rigorous testing has demonstrated its ability to reduce chamber temperature by 5.5°C in just 35 minutes, using a modest 12V 7Ah battery. Beyond its environmental benefits, this solar refrigerator offers long-term cost-effectiveness and reliable performance. It is well-suited for a variety of applications, including rural areas, outdoor activities, and off-grid living.**

Keywords— **R134a refrigerant, solar-powered refrigerator, low voltage, remote areas, sustainable development.**

I. INTRODUCTION

The scarcity of reliable electricity in isolated rural areas poses significant challenges for food and medicine preservation, jeopardizing public health and food security. To address this pressing issue, innovative solutions are urgently needed.

This research presents a novel approach to enhance refrigeration access in off-grid regions: converting traditional refrigerators into standalone models powered by renewable energy sources. By adapting the compressor to operate on low-voltage direct current, we have not only made this technology compatible with solar power but have also optimized its performance in terms of cooling capacity and energy efficiency [4].

Our objectives are twofold: to demonstrate the technical and economic feasibility of this modification and to evaluate the performance of the adapted refrigerator. This sustainable and accessible solution could revolutionize refrigeration systems in remote areas. Technological advancements have paved the way for adapting traditional appliances to renewable energy sources ([12], [14]), and studies have consistently highlighted the critical role of renewable energy in improving access to essential services like refrigeration ([6], [8], [11]).

Economic viability is another crucial factor. Cost-benefit analyses have shown that solar-powered solutions can be cost-effective in the long term, particularly in regions with abundant sunlight [10]. Moreover, case studies have demonstrated the positive impact of solar-powered refrigeration on local economies and health outcomes ([3], [7]).

To ensure the reliability and efficiency of the adapted refrigerator, we conducted a thorough performance evaluation. Previous research has provided valuable insights into the performance metrics of solar-powered refrigeration systems ([2], [13]), and studies have explored strategies for optimizing energy consumption in solar-powered appliances ([4], [12]).

This research aims to address the critical need for sustainable and accessible refrigeration solutions in isolated rural areas. By demonstrating the feasibility and performance of a solar-powered refrigerator, we offer a practical and innovative approach to overcoming the challenges of food and medicine preservation in off-grid communities. Our findings contribute to the growing body of knowledge on sustainable energy solutions for rural development ([5], [9], [11]).

II. MATERIALS AND METHODS

A. Description of Components of Classic Refrigeration System

A classic refrigeration system primarily consists of a compressor, a condenser, an expansion valve, and an evaporator. These components interact to ensure the cooling cycle.

- Compressor: The heart of the system, the compressor compresses the vapor of the refrigerant, thereby increasing its pressure and temperature.
- Condenser: This heat exchanger rejects the heat from the refrigerant to the outside, transforming it into a liquid.
- Expansion Valve: The expansion valve abruptly reduces the pressure of the liquid refrigerant, causing it to partially evaporate. This expansion results in a significant drop in the temperature of the refrigerant.
- Evaporator: Placed in the space to be cooled, the evaporator absorbs heat from the environment, causing the refrigerant to evaporate.

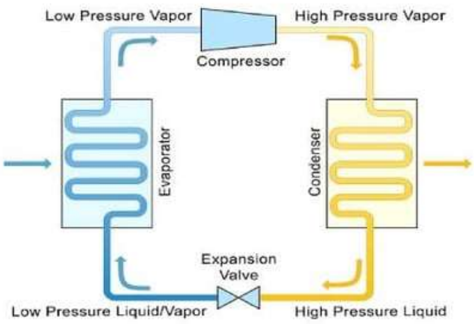

Fig.1 Classic refrigeration system diagram [15]

B. *Description of the Refrigerator Modification*

The original refrigerator, operating on alternating current (AC) with a nominal voltage of 110 to 230 V AC and a frequency of 50 Hz, was modified. It had a capacity of 115 liters for refrigeration and 5 liters for freezing. The parts salvaged from the old refrigerator include the refrigerator cabinet, the evaporator, and one part of the compressor.

1. Compressor Modification

To adapt the refrigerator to a 12 - 24V power supply, we modified the compressor.

The compressor's original electrical part was removed and replaced with a new motor, while the mechanical portion (piston, cylinder, and shaft) were retained. This modification reduced the overall weight of the compressor and allowed for a more efficient operation at lower voltage.

2. New Drive System

The cooling system's core component is a cylindrical brushed DC motor, specifically designed for this application. Its compact, robust design and ability to deliver high torque at low speeds make it ideal for driving the compressor.

With a maximum power output of 38 Watts, this motor ensures optimal compressor performance. Measuring 16.5 cm by 7.5 cm, its compact size facilitates seamless integration into the system. The motor generates a torque of 1-3 Nm, sufficient for efficient refrigerant compression.

Operating on 12-24 Volts, the motor adapts to various power sources, including solar panels. Its 2.5 cm shaft directly couples to the compressor via a mechanical coupling, located 4 cm from the base of the shaft, optimizing power transmission and minimizing mechanical losses.

When activated, the motor converts electrical energy into mechanical energy, driving the compressor. This compression process increases the refrigerant's pressure and temperature. The heated refrigerant is then condensed, releasing heat. The liquid refrigerant expands, evaporating and absorbing heat. The cooled vapor subsequently absorbs heat from the environment before returning to the compressor to initiate another cycle.

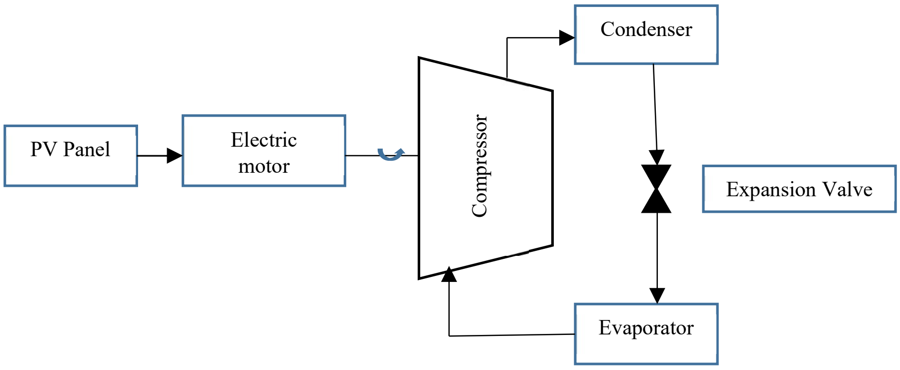

Fig.2 Schematic diagram for the solar-powered refrigeration system.

3. Refrigerant Type

R134a was selected as the refrigerant due to its numerous advantages, including safety, performance, compatibility, availability, and cost. It is non-toxic, non-flammable, and offers good thermodynamic properties, making it suitable for various applications. R134a is widely compatible with materials used in refrigeration systems and remains easily obtainable. Historically, R134a was adopted as a replacement for CFCs and HCFCs, which were harmful to the ozone layer. While newer refrigerants with very low global warming potentials are being developed, R134a continues to be a viable option for many applications, especially in existing systems.

4. Advantages of the Modification

This modification offers several benefits, including:

- Adaptability: Allows the refrigerator to operate on a new power source (12V to 24V battery), making it more suitable for mobile use or standalone applications.
- Energy Efficiency: Reduces electrical consumption by utilizing a more efficient DC motor.
- Simplified Maintenance: Separates the mechanical and electrical components of the compressor, simplifying maintenance tasks.

C. System Preparation

To prepare the system, it was initially evacuated for at least 5 minutes while running the compressor with all components present. This vacuum process removes any residual air or moisture from the refrigeration circuit, ensuring refrigerant purity and preventing corrosion. During the vacuum phase, a leak detector was used to verify the integrity of the entire circuit. Once the absence of leaks was confirmed, the circuit was filled with R134a refrigerant using a precise electronic scale. The amount of refrigerant introduced was determined by the circuit's volume and the compressor's specifications, following the manufacturer's recommendations.

D. Instrumentation

To conduct the experiments, a stabilized and adjustable power source was used to vary the supply voltage of the compressor motor and assess its impact on system performance. A voltmeter measured the voltage across the motor terminals, while an ammeter recorded the current drawn by the motor. A tachometer was employed to measure the motor's rotational speed. Additionally, thermometers were used to monitor temperatures at different points within the refrigeration circuit, including the suction line, discharge line, evaporator, and condenser.

E. Experimental Procedure

To initiate the experiment, the compressor was connected to a stable power source. Prior to recording measurements, the system was allowed to reach a steady state.

The supply voltage to the motor was gradually adjusted, and the corresponding values of current, rotational speed, and temperatures at different points within the circuit were noted.

Measurements were taken at regular intervals over an extended period to ensure statistically reliable results.

F. Data Processing

To analyze the system's behavior, we plotted the curves representing the variation of different physical quantities against the supply voltage. By examining these results, we were able to draw conclusions about the refrigeration system's performance under varying conditions.

G. Sizing and Installation

1. Solar System Sizing

To guarantee sufficient energy autonomy, we designed a solar system comprising a 100 Ah battery, a 10-20 A charge controller, and a 150 W photovoltaic panel. The battery capacity was selected to accommodate the refrigerator's daily energy consumption and the local solar conditions. The charge controller protects the battery from overcharging and optimizes solar panel charging. The photovoltaic panel's power rating was determined based on the refrigerator's consumption and the energy conversion losses.

2. Component Sizing

    a. Compressor

For our prototype, we selected a volumetric piston compressor, known for its simplicity and durability. This type of compressor effectively converts the rotary motion of the motor into the reciprocating motion required to compress the refrigerant.

    b. Condenser

In our project, we opted for a static air condenser. This component operates on the principle of natural convection: the hot refrigerant, circulating through a coil, transfers its heat to the ambient air. This heat exchange allows the fluid to liquefy.

The static air condenser offers simplicity, reliability, and quiet operation due to its lack of moving parts. However, its performance can be limited by ambient temperature and the available heat transfer surface. Despite these limitations, it remains a suitable choice for many cooling applications, especially in environments where space is constrained and noise reduction is crucial.

For this small-scale installation, the fluid is expected to circulate at an average velocity of 5 m/s within the discharge line (inside the condenser).

The condenser measures 42 cm by 50 cm. This heat exchange surface area was carefully selected to meet the required cooling capacity and accommodate the specific ambient conditions of the intended application.

The tube, with a cross-sectional area of 6 mm^2, was sized to optimize heat transfer efficiency while minimizing pressure drop within the system.

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Fig.3 Static condenser

c. Expansion valve

A capillary tube expansion valve was selected due to its simplicity of design and relatively low cost. The capillary tube operates by restricting the flow of refrigerant. By reducing the pressure at the inlet of the evaporator, the refrigerant undergoes an adiabatic expansion, resulting in a decrease in temperature and a change of state from liquid to vapor.

A desiccant is integrated upstream of the capillary tube. Its essential role is to ensure the quality of the refrigerant by removing any traces of moisture. Moisture present in the refrigeration circuit can lead to the formation of ice in the evaporator, reducing the efficiency of the system and potentially damaging the compressor. The desiccant, typically consisting of molecular sieve or silica gel, absorbs moisture, thereby protecting the system.

Fig.4 Desiccant dryer and capillary tube

Evaporator

An air-cooled static evaporator was selected for its simplicity and quiet operation. The evaporator, measuring 30 cm x 40 cm, is designed to facilitate natural convection heat transfer, eliminating the need for a fan. Its dimensions were determined based on the required heat load to ensure optimal performance

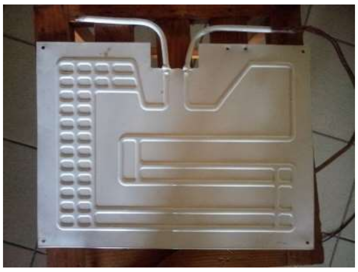

Fig. 5 Static evaporator

3. Installation

a. Welding

The selection of welding method is contingent upon the specific application. Hard soldering, which involves melting both base metals and a filler metal, is indispensable for refrigerant joints that must withstand high pressures. Soft soldering, a lower temperature process, is suitable for secondary circuits such as water or air lines where the joint does not need to withstand extreme conditions.

b. Installation Steps

Before soldering, surfaces must be thoroughly cleaned to ensure proper filler metal adhesion. Components should be assembled according to specified diagrams and dimensions. Soldering should be performed with care, ensuring gradual and uniform heating. A leak detector should be used to verify the absence of leaks before commissioning.

Commissioning involves creating a deep vacuum to remove residual air and moisture from the refrigeration circuit. The precise quantity of refrigerant, determined through thermal calculations, should then be introduced into the system.

III. RESULTS AND DISCUSSION

A. Results

This study aimed to adapt a traditional AC compressor to operate on low-voltage direct current. To achieve this, we replaced the original motor with a suitable DC motor and modified the electrical circuit accordingly.

1. Characterization of the Modified Compressor

Measurements taken on the modified compressor established the voltage-current-rotational speed characteristic curves (Table). These results show a direct correlation between the applied voltage and the motor's rotational speed, as well as an increase in current intensity with speed.

Table. Voltage-Current-Rotational Speed Characteristics of a Modified Compressor

Voltage (V)	Current (A)	Rotational Speed (rpm)
12	3	1300
18.04	2.8	1934
20.8	2.6	2006
22	2.3	3003
23.33	2.1	3742
24	2	3830

A comparative analysis of two refrigeration systems reveals significant differences in energy consumption. The original system consumes 211.2 watts at startup and 209 watts during normal operation. In contrast, the new modified system, equipped with a variable speed and voltage compressor, exhibits a much lower consumption, ranging between 36 and 56 watts. This substantial reduction in energy consumption is attributed to the new system's ability to adapt its power output to actual needs, resulting in significant energy savings, particularly during continuous operation.

2. Operational Test

An operational test was conducted by powering the compressor with a 12V 7Ah battery. The compressor successfully lowered the temperature of the test chamber by 5.5°C in 35 minutes, with an average consumption of 4.6 A. (P=12V*4.6 A== 55.2W)

3. Calculation of the Coefficient of Performance (COP)

The COP, a key indicator of the system's energy efficiency, was calculated based on the measurements. It is defined as the ratio of the heat extracted from the cold reservoir (Qcold) to the work input (W). A higher COP signifies greater efficiency. The calculated COP of 12.6 suggests that the modified system demonstrates acceptable energy efficiency.

B. Discussion

The results obtained demonstrate the feasibility of modifying an AC compressor to operate on direct current. Adapting the compressor has yielded satisfactory performance in terms of cooling and energy consumption. However, several points warrant further investigation:

1. Energy efficiency

While the obtained COP is encouraging, it would be interesting to compare this value with that of a commercial refrigeration system operating on alternating current to assess potential gains in energy efficiency.

2. Compressor lifespan

The modifications made to the compressor could impact its lifespan. Long-term tests would be necessary to evaluate the reliability of the modified system.

3. Optimization

There are numerous opportunities to optimize the system, including the choice of refrigerant, the sizing of components, and the control of the compressor speed.

4. Economic Analysis

Modifying an existing refrigerator presents a sustainable and cost-effective option. This approach significantly reduces the environmental impact associated with manufacturing and disposing of a new appliance, while also offering substantial financial savings. The estimated cost is more than 85% lower than purchasing a new commercial AC refrigerator.

5. Impact of Technological Choices

Motor selection directly influences a system's energy efficiency. While brushed DC motors offer simplicity and cost-effectiveness, their frictional losses compromise efficiency. Brushless motors, eliminating brush-related losses, could enhance the system's energy performance. However, their integration necessitates more intricate power electronics, incurring additional costs.

C. Perspectives

This study opens up interesting prospects for the development of autonomous refrigeration systems powered by renewable energy sources. The obtained results are encouraging and suggest that modifying existing compressors is a viable solution to reduce energy consumption and decrease the environmental impact of refrigeration.

IV. CONCLUSION

This research successfully demonstrated the feasibility and benefits of modifying a traditional refrigerator into a low-voltage model. The resulting prototype exhibited comparable cooling performance to commercial appliances. Its 12-24V power supply, coupled with renewable energy sources, offers significant autonomy, making it ideal for off-grid applications. Moreover, the economic viability of this solution is enhanced by the reuse of existing components. By reducing energy consumption and promoting renewable energy, this approach contributes to environmental sustainability.

Future prospects for this technology are promising. Potential optimizations, such as improved insulation and advanced control systems, could further enhance the efficiency of these refrigerators. Additionally, this solution could be adapted to various applications, ranging from domestic use to professional settings. Integrating these refrigerators into local energy systems, combining solar panels and batteries, presents opportunities for creating autonomous and sustainable systems.

To facilitate the widespread adoption of this technology, especially in developing countries, training local technicians is crucial.

In conclusion, modifying traditional refrigerators to adapt them to low-voltage power supplies is an innovative and promising solution for meeting refrigeration needs in diverse contexts. The findings of this research pave the way for new applications and future developments, contributing to a more sustainable future.

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