

Cooling Load Analysis of a Household Refrigeration System: Evaluating the Impact of Compressor Efficiency

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ABSTRACT

This research explores the cooling load and compressor performance in a R600a-based household refrigeration system, focusing on energy efficiency and thermal optimization. A refrigerator with two compartments was studied, which combines the thermodynamic model and experimental evaluation to assess the cooling demand and compressor work. The total cooling load, including transmission, product, and infiltration loads, accounted for 70.087W. Freezer and refrigerator temperatures were recorded at -19.84°C and 4.06°C while energy consumed was 56–58W compared to the specified 100W with suction and discharge temperatures of 32 and 54°C. However, the 130W compressor was rated at 66 ~70W with suction and discharge temperatures of 38°C and 63°C respectively with marked inefficiencies. The selection of materials was of particular importance for the performance. High R-value polyurethane foam insulation was able to cut thermal conductivity by 50%, thus saving energy by lowering cooling loads. The overall thermal management was further improved by the use of cold-rolled steel panels and polystyrene liners, the latter ensuring high strength and excellent insulation. The calculations for product and infiltration loads showed how the cooling efficiency might be affected by the ambient conditions and the thermal characteristics of the stored items. The findings confirm that a 100 W compressor is the most optimal choice for domestic refrigerators for this model since it performs well with a duty cycle of 70%, providing cooling in an energy-efficient way. This study brings out the role of advanced insulation materials and compressor technologies that are efficient in reducing energy consumption. Future developments will revolve around the use of variable-speed compressors and energy recovery systems to better cope with fluctuating operational requirements, thus contributing to international energy conservation standards and the furtherance of sustainable refrigeration technologies.

Keywords: Cooling Load, Compressor, Performance Evaluation, Power Consumption, Safety Factor.



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1. Introduction

Growing energy consumption needs drive manufacturers towards optimally designed fridges. Numerical simulations come as more efficient when compared to the test and adjust methods. Although there are numerous modeling approaches, many have issues in terms of computational complexity and the quality of the results attained [1]. High costs of energy draw attention to the efficiency of form and function in industrially made home freezing and refrigeration. These units have low cooling power (50-250W), small charge, sealed circuit, and capillary tubes which provide the best performance with on-off type controls [2]. At the beginning of 1980, simulation models for refrigeration systems were proposed where the main emphasis was placed on air conditioning and heat pumps [1]. Effective design of individual system components and good component matching determine a residential refrigerator's initial and ongoing costs [3]. Cycling control operates home refrigerators, turning on compressors at certain temperatures. When it is inoperative, the vast majority of refrigerant remains concentrated in the compressor and evaporator while the condenser holds only superheated gas. The flow of the refrigerant towards the condenser catches liquid in the accumulator while denying the evaporator at the same time. Refilling starts as soon as a thin layer of liquid is observed at the condenser's outlet [2]. Control of compressor cycling

linked with the cooling load and cut-in/cut-out temperatures allows for reducing energy consumption and overcooling. Sophisticated modeling leads to effective and accurate calculations in refrigerant control, minimization of wasted energy, performance optimization, and contemporary conformity as well as encouragement of manufacturing sustainability to home refrigeration systems [4]. The paper also outlines successful practices, cost optimization, and emerging technologies, and leads organizations while providing them on sustainable production and energy management.

Nicoletti et al. [5] proposed aircooled passive system helps to improve the efficiency of the refrigerator by making use of the external air, raising the efficiency of the refrigerator used in cold climate by 36%. Nicoletti has also discussed on the fact that passive cooling helps to cut both compressor load and energy consumption though not very effective in warm climate. Further investigation is needed as adiabatic cooling works well in certain loads and climate. Tu et al. [6] investigated a real regenerated air refrigerator for cooling load and COP by utilizing finite-time thermodynamics. There was an enhancement in conductance by using a better heat exchanger but the pressure ratio and the efficiency of the compressor have not yet been tested experimentally. In an attempt to improve the COP to integrate the Brayton cycle, Tu et al. recommended an

enhanced Brayton cycle that needs far-reaching experimental investigation in real-life applications. Elarem et al. [7] studied that addressed increasing energy efficiency of refrigerators and regulating temperature through Phase Change Material (PCM). A new PCM heat exchanger further improved COP by 8% and decreased in power output by 12%; the positioning of PCM was optimized for improved thermal performance. Boban et al. [8] identified the role of geothermal energy as a sustainable source of energy meeting increasing energy needs. The authors' decision represents research priorities for GHEs, with an emphasis on deep vertical BHEs, design parameters, and working fluids to enhance compressor efficiency and energy effectiveness. Alawadhi and Phelan [9] facilitate a study on high ambient temperature (HAT) residential vapor-compression air conditioners, adopting 40 °C as the threshold for rating low GWP refrigerants. Condensers increased the COP between 18 to 50% but, A2L refrigerants lower the efficiency. New development work should be devoted to further enhancing the heat exchangers and compressor control system for improved heat rejection. Yoo [10] proposed an analytic model to increase the quality of household fridges was developed by talking about kinds of GHE and economic aspects to increase efficacy and diminish cooling loads.

Several research projects have been conducted on refrigeration systems, but the studies relating to refrigeration systems are very limited in research to consider dynamic cooling load analysis, the latest insulation materials, and practical validations of compressor performances. This study addresses these gaps by integrating experimental and thermodynamic techniques to enhance energy by concentrating on the material and the compressor. The main target of this study is explore the cooling load and compressor performance in a R600a-based household refrigeration system, focusing on energy efficiency and thermal optimization. The study is done using two types of compressors by selecting the capacities of 130W and 130W. Also, the aim is to promote the development of efficient and environmentally friendly refrigeration systems at an international level.

2. Methodology

This study focuses on a household refrigerator with two compartments: two sections or cases: one for refrigeration or cooling the temperature of the foods, and the other for freezing some of the foods. The analysis looks at the system as two parts: the cabinets and the refrigeration loops. A refrigerator section maintains food temperature at an average of 5 °C. Whereas the freezer maintains a temperature of about - 18 ° C [11]. The freezer compartment is located at the top, and the fresh food is below it. Fig. 1 shows the design overview of the refrigerator model and the foaming thickness of the domestic refrigerator.

2.1 Material selection

Polyurethane foam regulates the amount of cooling load in a refrigerator through the restriction of the interaction of heat within the interior and exterior environments [15]. Polyurethane foam thereby insulates to reduce the cooling load, ease the work of the compressor, save energy, and bring down costs. High R-value guarantees top-notch thermal performance regarding utility costs and the environment [16]. Refrigerator side panels are made of cold rolled steel sheets both for tensile strength and surface finish and polystyrene

(PS) liners offer thermal insulation. The cold rolling steel has good thermal conductivity [17]. Refrigerator attributes consist of single-speed compressor, direct cooling type evaporator, and side-mounted condenser; the detailed specification is listed in Table 1.

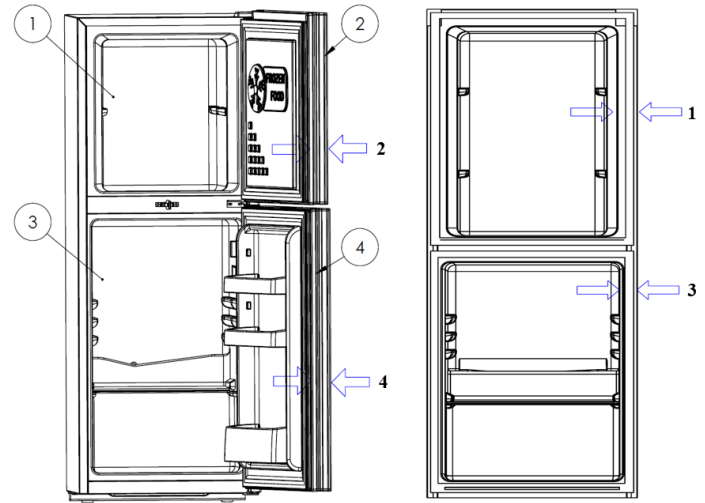


Fig. 1 Illustration of the front view of household refrigerator with different parts and foaming thickness insulation

Table 1 Detail specification of the household refrigerator.

Part No	Part name	Dimension (mm×mm)	Foaming thickness (mm)
1	Freezer cabinet	568 × 327	85
2	Freezer door	667 × 487	75
3	Refrigerator cabinet	601 × 389	55
4	Refrigerator door	678 × 487	50

2.2 Refrigerator and freezer performance standards

Energy efficiency standards, refrigerator design, and climate classes are vital in the classification of these products that have wide applications in the modern world [12]. Energy labels, including energy star and EU energy labels, are meant to help in energy conservation. Refrigerators are available in different categories depending on storage requirements, and climate classes for worldwide use [13, 14]. The refrigerator classifications and climate classes are listed in Table 2.

Table 2 Refrigerator classifications and climate classes [14].

Climate Class	Environment	Fresh Food Cabinet	Freezer Cabinet
SN	Cool	0 ~ +8 °C	≤ 0 °C
N	Moderate	0 ~ +8 °C	-6 °C
S	Warmer	+10 ~ +32 °C	-12 °C
ST	Hot and humid	+10 ~ +32 °C	-18 °C
T	Very warm	+10 ~ +43 °C	-18 °C

2.3 Equations

Transmission load: Sensible heat gain through walls, floor, and ceiling is calculated at steady state as [18].

$$q = U A \Delta t \quad (1)$$

The overall coefficient of heat transfer U of the wall, floor, or ceiling can be calculated by the following equation [17].

$$U = \frac{1}{\frac{1}{k_i} + \frac{x}{k} + \frac{1}{k_o}} \quad (2)$$

The major refrigeration load results from heat production by-products to be stored like fruits and vegetables and the electrical energy that is used to cool them to the required temperatures for storage [15]. The following formula can be used to determine how much heat has to be removed [15].

a) The heat removed to cool from the initial temperature to some lower temperature above freezing:

$$Q_1 = mc_1 (t_1 - t_2) \quad (3)$$

b) The heat removed to cool from the initial temperature to the freezing point of the product:

$$Q_2 = mc_1 (t_1 - t_f) \quad (4)$$

c) The heat removed to freeze the product:

$$Q_3 = mh_{if} \quad (5)$$

d) The heat removed to cool from the freezing point to the final temperature below the freezing point:

$$Q_4 = mc_2 (t_f - t_3) \quad (6)$$

Accumulation and equipment load can be more than 50% of refrigeration load [20]. Infiltration is due to the density of air and takes in air equal to the quantity out together with condensed moisture. Cold rooms that are not well sealed allow air through the door [21]. Here air change through doorways contributes to heat gain as follows:

$$q_i = qD_i D_f (1 - E) \quad (7)$$

The following air exchange equation is for a fully established flow [22]:

$$q = 0.221A (h_i - h_r) \text{ pr } (1 - \rho_i/\rho_r) 0.5 (gH) 0.5 F_m \quad (8)$$

The density factor is defined as:

$$F_m = \left(\frac{2}{1 + (\rho_r/\rho_i)^{1/3}} \right)^{1.5} \quad (9)$$

2.4 Experimental setup

Fig. 2 shows the experimental setup of the household refrigerator by mentioning the sensor position inside the cabinet. To make it simple, we have located six positions for six sensors in the cabinet whose positions are illustrated (Fig. 2) and listed (Table 3); three for the freezer compartment and three for the refrigerator compartment. The procedure assesses the cooling ability of a refrigerator plus the moisture removal abilities at 33°C and 55 % RH through accurate measurement of the thermal performances of six sensors used for temperature and humidity. We collect the data by logger which provides a live view of sensor data, trends, and status along with control and exporting options. We conducted our experiment in the humidity and cooling control chamber, where we can precisely regulate the ambient temperature, humidity, and operating voltage. To

ensure the reliability of our setup, we performed the test six times inside the chamber. Finally, to sum up this result, the tests data are collected by averaging the all experiments.

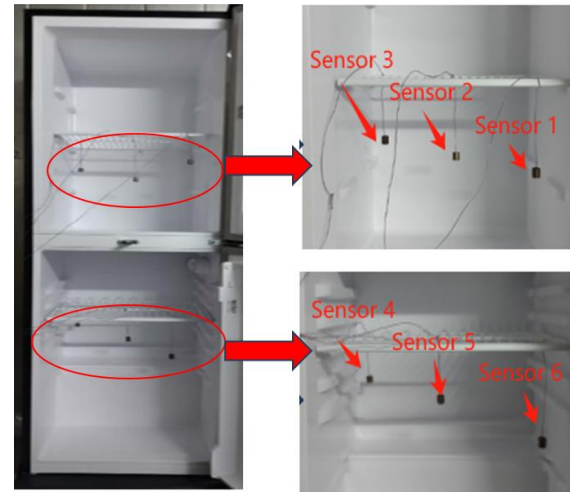


Fig. 2 Experimental setup of household refrigerator

Table 3 The position of the sensor.

Sensor	Cabinet	Position	Measurements
1	Freezer	Front	30mm from side, 150mm up
2	Freezer	Middle	Cabinet center, 150mm up
3	Freezer	Back	30mm from side, 150mm up
4	Refrigerator	Front	30mm from side, 150mm up
5	Refrigerator	Middle	Cabinet center, 150mm up
6	Refrigerator	Back	30mm from side, 150mm up

3. Calculations

This study uses cold-rolled steel (CRS) for improved heat transfer in refrigerator panels, polystyrene (PS) for insulation, and polyurethane foam for enhanced thermal efficiency, reducing heat transfer, and improving energy conservation.

$$R_{\text{side}} = \frac{\text{Thickness}}{\text{Thermal Conductivity}} = \frac{0.5}{155} = 0.0032258 \text{ K/W}$$

$$R_{\text{liner}} = \frac{\text{Thickness}}{\text{Thermal Conductivity}} = \frac{1}{2.3368} = 0.428507 \text{ K/W}$$

$$R_{\text{polyurethane}} = \frac{\text{Thickness}}{\text{Thermal Conductivity}} = \frac{70}{0.023} = 1739.1304 \text{ K/W}$$

$$R_{\text{total}} = 0.0032258 + 0.428507 + 1739.1304 = 1739.56 \text{ K/W}$$

$$\text{Total Transmission load } Q_{tr} = 31.61 \text{ W}$$

To calculate the product load, involve cooling from 30°C to 4°C, freezing for 3 h (specific heat of lean beef: 3.49 kJ/kg·°C), latent heat of freezing: 233 kJ/kg, cold storage to -18°C: 1.94 kJ/kg·°C.

$$\text{To cool from 30 to 4°C in a chilled room} = 529.074 \text{ kJ}$$

$$\text{To cool from 4°C to freezing point in freezer} = 122.094 \text{ kJ}$$

$$\text{So, freezer} = 6.3 \times 233 = 1467.9 \text{ kJ}$$

$$\text{To cool from freezing to storage temperature} = 169.344 \text{ kJ}$$

$$\text{Total Product load for refrigerator} = 2288.412 \text{ kJ} = 26.50 \text{ W}$$

For the product load of the freezer, we consider vegetables (4.35 kg, specific heat 3.67 kJ/kg·K), with a 27°C temperature difference, the product load is 5.2 W.

Hence, the total product load $Q_{pl} = 26.5 + 5.2 = 31.7W$

For infiltration load estimation, use an ambient temperature of 33°C, and cabinet temperature of 5°C as well as substitute the air property values in equation 8 to obtain an accurate infiltration load as indicated below:

$$F_m = 0.985 \text{ \& } q = 1.659W$$

To estimate infiltration load, express ambient temperature as 33°C, cabinet temperature as -18°C, and substitute air property as required in Eq.(8) to assess the cooling load precisely.

$$F_m = 0.951 \text{ \& } q = 5.128 W$$

Total Infiltrations load $Q_{if} = 6.787 W$

Total cooling load is = 70.087 W

Considering the safety factor =77.0087 W

Appreciation keeps on varying but at times operates at 70% when refrigeration is in use most of the time. A 100W compressor performs with a 70.087W load, while the 130W compressor operating time will be 54% of the time. This study compared the performance of both a 100W and a 130W compressor for the same refrigeration system. This was done to evaluate the efficiency of each of the compressors under test conditions in terms of cooling effect and energy used.

3.1 Error and uncertainty analysis

In order to determine the uncertainty for all the components of the cooling load, it is going to make use of the uncertainty propagation equation by considering 2% of the safety factor [23]:

$$u_c(Q_{total}) = \sqrt{u^2(Q_{tr}) + u^2(Q_{pl}) + u^2(Q_{if}) + u^2(S_f)} \quad (10)$$

The total cooling load, including the safety factor, is $Q_{total} = 77.0087 W$ with a combined uncertainty of $u_c(Q_{total}) = \pm 2.8W$. The uncertainty of the sensor and RH are $\pm 1^\circ C$ and $\pm 5\%$, respectively.

3.2 Compressor specification

According to the calculation, we selected two resistance start-capacitor run (RSCR) type compressors for this test, while the specifications of the selected compressor are listed in Table 4.

Table 4 The detailed specifications of the compressor [24].

Capacity (W)	Power (W)	COP	Displacement
100	75	1.58	6 cm ³
130	98	1.62	7.2 cm ³

4. Results and discussion

The 100W compressor model recorded improved thermal efficiency, settling at -19.84 °C for the freezer compartment and 4.06 °C for the fridge compartment using 56-58W power. It was worse with the 130W compressor, which reached -17.37°C and 7.11°C with 66-70W.

4.1 Performance evaluation for 100W compressor

Fig. 3 indicates the cooling behavior of the freezer and refrigerator systems. The freezer's temperature drops from

33.52°C to -19.06°C by 01:50 and this is good heat extraction. During stabilization (01:50~04:00), it stays at -19°C and, at the end of the period, it cools to -19.84°C, thus supporting constant cooling temperatures. Meanwhile, the refrigerator's temperature drops from 33.71°C to 5.55°C by 02:20, with some fluctuations because of the compressor cycling at 4.56 °C to 6.17 °C and getting stable at 4.06 °C by 04:00 implying that the room isolated necessary heat load needed for cooling.

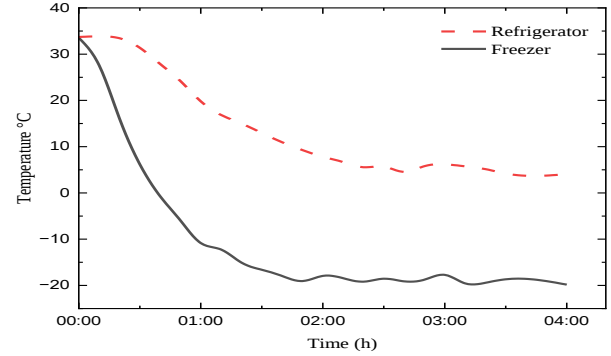


Fig. 3 Refrigerator and freezer temperature trend with time with 100W compressor

Fig. 4 illustrates the suction and discharge temperature of the compressor trend with time with a 100W compressor. The suction temperature is found of the average value is 32°C, while the standard for the R600a refrigerant is 30°C ~ 34°C. Again, the average value of discharge temperature is 54°C, while the standard for the R600a refrigerant is 50°C ~ 55°C.

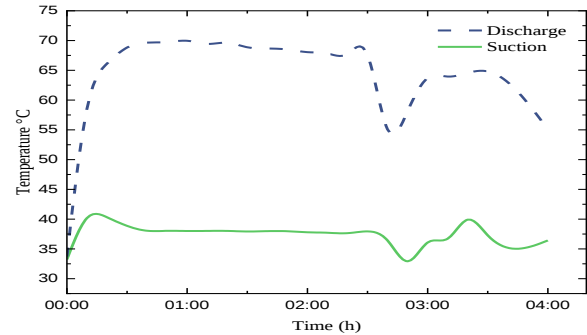


Fig. 4 Suction and discharge temperature of compressor trend with time with 100W compressor

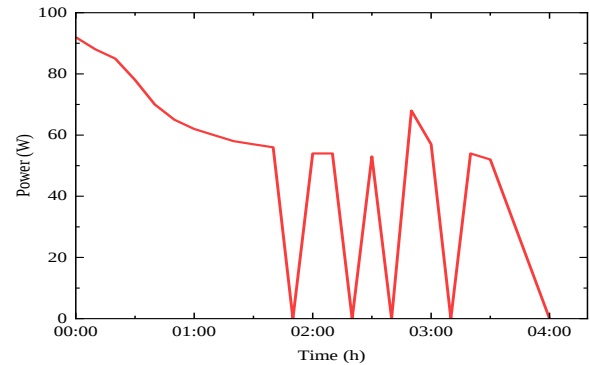


Fig. 5 Power consumption of 100W compressor

Fig. 5 shows the power consumption of the refrigeration system over four hours, starting at 92W at 00:00 as the inline compressor starts to rapidly cool the system. Power

gradually decreases to 56W by 01:40 because as pointed out earlier, the cooling demand declines. At 01:50 the compressor has entered a cutoff state with a power of 0W the signal that the system has attained the desired temperature. During operation, power can vary up to 54 W~ 68 W while short bursts are to cool down to 0 W to manage the temperature condition. By 03:50 power, consumption was reduced to 52W for a manifestation of the use of energy. This cycling behavior shows good load control and low power consumption while satisfying the cooling function.

4.2 Performance evaluation for 130W compressor

Fig. 6 illustrates the cooling behavior of both the freezer and refrigerator systems. The freezer's temperature drops from 33.36°C to -20.21°C by 02:03 in terms of the heat dissipation feature, an indication of an efficient cooling system. After reaching -19.12°C at 01:50, then it reaches -5°C at 02:03, afterwards, it is a more consistent temperature of -20.21°C, which is lower than the desired -18°C. The system goes into cycling, and the temperatures flow between -17.38°C and -19.33°C before settling at -17.37°C signifying normal compressor cycling. For the refrigerator, the temperature drops from 33.65°C to 8.61°C by 01:50, it supports to 7.03°C at 02:03. It oscillates between 6.12°C and 7.98°C.

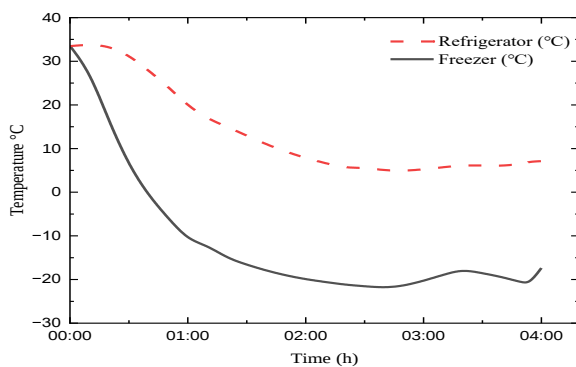


Fig. 6 Refrigerator and freezer temperature trend with time with 130W compressor

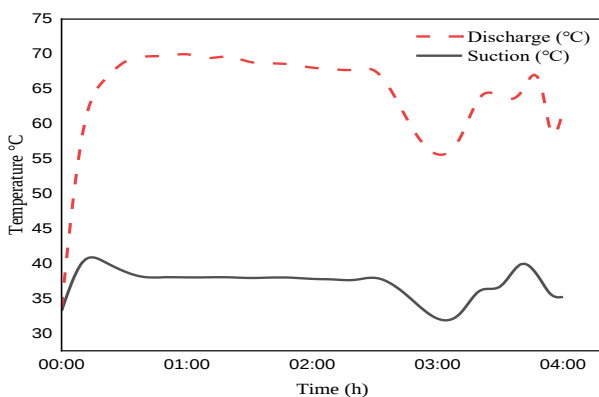


Fig.7 Suction and discharge temperature of compressor trend with time with 130W compressor

Fig. 7 illustrates the suction and discharge temperature of the compressor trend with time with a 130W compressor. The suction temperature is found the average value of 38 °C, while the standard for the R600a refrigerant is 30°C ~ 34°C. This indicates the 130W compressor maintains the proper suction temperature value. Again, the discharge temperature, average value is 63°C, while the standard for the R600a

refrigerant is 50°C ~ 55°C. This indicates the 100W compressor maintains the proper discharge temperature value.

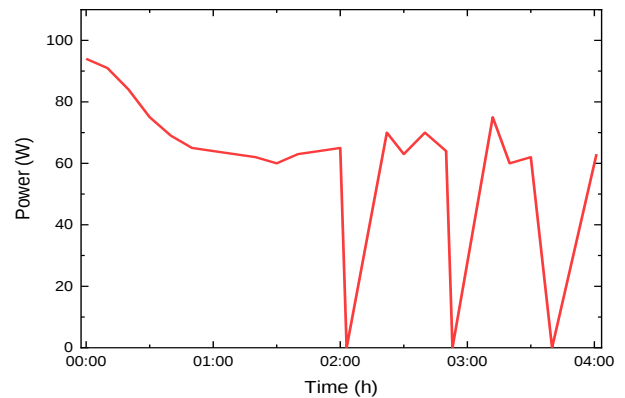


Fig. 8. Power consumption of 130W compressor

Fig. 8 shows the power consumption of the 130W compressor, starting at 94W and dropping to 40W by 02:00. Power fluctuates between 60W-70W, with intermittent drops to 0W at 02:00, 02:53, and 03:40 there may have been a cutoff of the compressor or some system stoppage. After initial declines, power stabilizes at 60-64W by 01:00 quite stable, but with fluctuations during the steeper parts (75W at 03:12). However, the design conditions are still violated; freezer temperatures of -17.37°C and refrigerator temperature of 7.11°C are achieved. This implies that the cooling capacities are low, and the energy consumption is far higher than the 100W compressor.

Overall, it is said that the 100W compressor demonstrates high cooling capability making the initial ambient temperatures of 33.52°C and 33.71°C cool to -19.84°C and 4.06°C in refrigerator with energy consumption of 92W during crank up and 50-60W standby. As the coefficient of performance (COP) is the ratio of the refrigeration effect (cooling load) to the power consumed by the compressor, the lower power consumption provides a large COP in getting the same refrigerating effect. Hence, the greater the COP value, the better the energy efficiency is the cooling process.

5. Conclusion

The investigation establishes the appropriateness of the 100W and 130W compressors for domestic refrigerator use and the enhanced energy efficiency of polyurethane foam insulation. This shows the experimental validation and opportunities of sophisticated technologies for fulfilling energy requirements. The specific findings are as follows:

- It is established that the efficiency of 100W and 130W compressors is confirmed on domestic refrigeration with calculated cooling load condition.
- The heat transfer coefficient of the refrigerator cabinet is decreased by 50% in the instance of the polyurethane foam insulation.
- The 100W compressor was more effective in cooling and consumed less energy (56 – 58 W).
- This model, the 130W compressor, used more power (66–70W) and marked it inefficiencies.

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NOMENCLATURE

q	Heat gain, W
A	Outside cross section area, m ²
U	Overall heat transfer coefficient, W/(m ² ·K)
x	Thickness of the wall, m
k	Thermal conductivity (wall material), W/(m·K)
h_i	Conductance of inside surface, W/(m ² ·K)
c_1	Sp. heat of product above freezing, kJ/(kg·K)
t_1	Initial temperature of product above freezing °C
ρ_i	Density of infiltration air, kg/m ³
F_m	Density factor
C_1	Sp. heat of product above freezing/(kg·K)
h_i	Conductance of inside surface, W/(m ² ·K)
m	Mass of product stored, kg