ISSN: 2141-2987

JOURNAL OF THE NIGERIAN INSTITUTION OF MECHANICAL ENGINEERS (JNIMechE)

Journal homepage: https://journal.nimechehq.org

Volume 13
Issue 01

Date Received: February 2024
Date Published: June, 2025

Development of a Split-System Refrigerator with Outdoor Condenser and Compressor Placement

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ABSTRACT

The term refrigeration is defined as the process of removing heat energy from a substance under controllable conditions, transferring heat from a lower temperature medium to a higher temperature medium, which according to the second law of thermodynamics, requires external work. Beyond its primary use for cooling and food preservation, refrigeration also provides thermal comfort in homes and offices. An experimental study was conducted using a 230V, 1Hp compressor with refrigerant R134, an 8 mm diameter condenser coil of 8.71 m length, and an evaporator box of 223.89 liters volume. Four scenarios were tested: with the outdoor unit inside the room with the refrigerator empty, outside the room with the refrigerator empty, inside the room with the refrigerator loaded, and outside the room with the refrigerator loaded. Results showed that the average room temperature was higher when the outdoor unit was inside the room, reaching 38.75°C at 270 minutes with the system loaded, compared to 34.5°C when unloaded. When the outdoor unit was outside, the room temperature was lower, at 33.5°C loaded and 35.25°C unloaded. Cooling effectiveness was better with the outdoor unit outside, achieving temperatures of -4°C and -12°C (unloaded and loaded respectively) compared to -2°C and -3°C when inside. The study concluded that placing the outdoor unit outside the room reduced the average room temperature by 10.97% when unloaded and by 4.95% when loaded, also significantly improving the coefficient of performance (COP) of the refrigeration system.

Keywords: Refrigeration; Coefficient of performance; Law of thermodynamics; Condenser; Evaporator; Compressor

1.0 INTRODUCTION

The desire to improve thermal comfort and preserve food has led to the development of appliances like fans, air conditioners, humidifiers, heaters, and refrigerators (Enteria et al., 2020). While these provide comfort and preservation, they also generate heat within living spaces. Hence, the need for an improved system. Thermal comfort, defined as a state of mind where an individual expresses satisfaction with their thermal surroundings, is influenced by factors like mood and culture. Humans maintain a stable core temperature through thermoregulation. Also, research has shifted from qualitative to quantitative analysis, with the PMV (Predicted Mean Vote) model, derived from Fanger's equation, as a foundational tool for assessing indoor thermal comfort. Enhancing thermal comfort involves building orientation, microclimate creation, and HVAC systems (Brager et al., 2015).

In addition, refrigeration systems (Figure 1) encompass vapor absorption, steam jet, and thermoelectric systems. The vapor absorption refrigerator was developed by Balzar von Platen and Carl Munters in 1922 and commercialized by Electrolux. Solar-based refrigeration systems have also been developed. Steam jet refrigeration systems use water evaporation in a low-pressure chamber to absorb heat (Krajčík et al,m 2022). Thermoelectric refrigeration systems, based on the Seebeck and Peltier effects, achieve low temperatures and are

used in electronic cooling. Hence, this research focuses on developing a split refrigerator with heat-generating components located outdoors, building on existing research indicating that conventional refrigerators contribute to thermal discomfort.

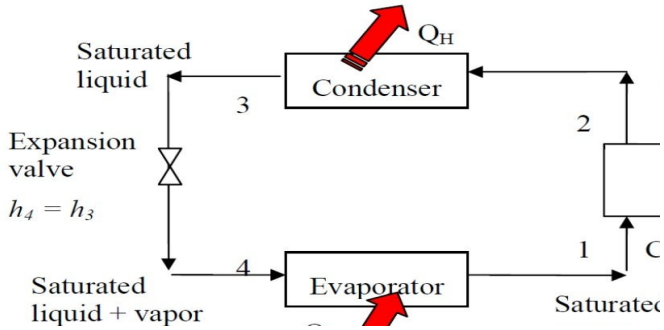


Figure 1: Refrigeration System (Mungyeko-Bisulandu et al., 2022)

Previous work on split refrigerators, such as the study by Lokendra et al. (2019), found that separating components resulted in a lower room temperature and a greater refrigerating effect. Lokendra et al. (2019) found the minimum average room temperature was 1.9% lower, and the refrigerating effect was 15.9% greater compared to a complete unit operating in one room. Additionally, Soni and Gupta [9] conducted an energy analysis of a vapor compression refrigeration cycle using refrigerants R404A, R407C, and R410A, deriving expressions for the Coefficient of Performance (COP). Nagalakshmi and Yadav [10] designed and analyzed a refrigeration system using refrigerants R12 and R134a. Suhane and Pandey [12] focused on energy management at the Jabalpur Hospital and Research Centre, conducting a comprehensive audit of electrical and thermal utilities. Prior work on split refrigerators has shown that separating the system components can lower room temperature and increase the refrigerating effect compared to a complete unit operating in one room. Studies have also focused on energy analysis of refrigeration cycles and energy management in facilities, including refrigeration systems. Therefore, this study contributes to this body of knowledge by developing a split refrigerator design to mitigate heat generation within living spaces.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials used in this research include;

i. Compressor: Operating at 250V, 50Hz, single phase, oil charged type with a capacity of 1 Hp, using refrigerant R-134A.
ii. Condenser: Air-cooled type, with a length of 8.71 meters and an outer diameter of 8 mm.
iii. Evaporator: Having a volume of 223.89 liters.
iv. Capillary Tube: Made of copper (Cu), 1.66 meters long, with a diameter of 5 mm.
v. Dryer (Filter)
vi. Rubber Seal
vii. Insulated Board
viii. Refrigerant: R-134a
ix. Fan: Operating at 220-240V, 50/60Hz, power consumption 5-6W, current 0.20A.
x. Hinges
xi. Mild-steel Plate
xii. Rivets
xiii. Angle Bar: Size 1½ inches.
xiv. Capacitor

xv. Pipe Fittings and Fasteners
xvi. Bolts and Nuts
xvii. Paint and Thinner

The main refrigeration system components such as the compressor, condenser, evaporator, and capillary tube, were essential for the vapour compression refrigeration cycle. The compressor compresses and transports the refrigerant vapor, the condenser removes heat from the refrigerant, the evaporator absorbs heat to produce cooling, and the capillary tube acts as the throttling device regulating refrigerant flow.

Other materials such as rubber seals, insulated boards, and various mechanical fasteners (hinges, rivets, bolts, nuts) were used to support the structural integrity and insulation of the system. The fan aids in air circulation, while the dryer/filter removes moisture and impurities from the refrigerant. The capacitor was used for starting or running the compressor motor. Paint and thinner are used for protective and finishing purposes.

2.2 Methods

2.1 Testing of the Refrigerator.

For the purpose of this experiment, four distinct scenarios were investigated to analyze the thermal and humidity behavior under varying conditions. The scenarios were designed based on two key variables: the location of the outdoor unit and the loading condition of the refrigerator. Specifically, the scenarios included:

i. The outdoor unit positioned inside the room with the refrigerator empty.
ii. The outdoor unit positioned outside the room with the refrigerator empty.
iii. The outdoor unit positioned inside the room with the refrigerator fully loaded.
iv. The outdoor unit positioned outside the room with the refrigerator fully loaded.

Also, throughout the experiment, several critical parameters were measured to assess the system's performance and its impact on the indoor environment. These parameters included:

i. Average Room Temperature (TR): This was calculated as the average of temperature readings taken simultaneously at four strategically selected points within the room, ensuring a representative measure of the overall room temperature.
ii. Evaporator Temperature (TC): The temperature at the evaporator coil was monitored to evaluate the cooling efficiency and thermal dynamics of the refrigeration system.
iii. Time Intervals: Measurements were recorded at regular intervals of 30 minutes to capture the temporal changes and trends in temperature and humidity.
iv. Relative Humidity (RH): The moisture content in the air was tracked to understand how the refrigeration system and unit placement influenced indoor humidity levels.

By systematically varying the location of the outdoor unit and the refrigerator load, and by monitoring these parameters over time, the experiment aimed to provide comprehensive insights into the thermal performance and environmental impact of the refrigeration setup under different operating conditions. However, the experimental procedures are presented below;

i. **Step 1:** On the first day, four thermometers were installed at strategic locations within the room, all positioned at the same height of approximately 2 meters above the floor. Additionally, one thermometer was placed inside the refrigerator cabinet, which was in an unloaded condition. The refrigerator was powered on for the experiment.
ii. **Step 2:** Immediately after setup, temperature readings of the room and relative humidity measurements of the outdoor air were taken using a flow meter at intervals of approximately 30 minutes. These measurements began simultaneously and continued for the same duration, with the outdoor unit located inside the room. The experiment commenced at 10:30 AM and concluded at 3:00 PM.

iii. **Step 3:** On the second day, with the outdoor unit still placed indoors, the refrigerator cabinet was loaded with 1 liter of water contained in a stainless steel container. A thermometer was placed inside the water to monitor its temperature. The experiment started at 10:20 AM and lasted for the same time interval and duration as in Step 2. During this period, temperature readings of both the indoor space and the refrigerator cabinet, as well as temperature and relative humidity of the outdoor air, were recorded.

iv. **Step 4:** On the third day, the outdoor unit was relocated outside the room. The experiment was set up as in Step 1 (unloaded refrigerator), and measurements were taken in the same manner as in Step 2. This trial began at 10:00 AM and ended at 2:30 PM.

v. **Step 5:** On the fourth day, with the outdoor unit still positioned outside the room and the refrigerator cabinet loaded with 1 liter of water, the measurements were repeated following the procedures of Step 2 and Step 3. The experiment started at 11:00 AM and concluded at 3:30 PM.

Figure 2 illustrates the complete setup of the fabricated refrigerator used in these experiments.



Figure 2: Complete Assemblage of the Split Refrigerator.

Refrigerating Efficiency of the Refrigerator;

Actual $COP_{ref} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{285.94 - 170.68}{328.62 - 285.94} = \frac{115.31}{42.68} = 2.702$

Carnot $COP_{ref} = \frac{TL}{TH - TL} = \frac{258}{328 - 258} = \frac{258}{70} = 3.686.$

Therefore,

Refrigerating Efficiency, $\eta_{ref} = \frac{\text{Actual COPref}}{\text{Carnot COPref}} = \frac{2.702}{3.686} = 73.30\%$

2.2. Evaluation of pipe lengths for the evaporator, condenser, and capillary tube

a. Length of Evaporator Pipe

Given:

Heat transfer rate, Qevap= 80.94W

Outer diameter, do= 0.008m

Inner diameter, di=0.007m

Outside heat transfer coefficient, ho=22.71W/m^2K

Temperature difference, ΔT=34−(−15) = 49K

Thermophysical properties of saturated liquid R134a at -15°C (from Lienhard and Lienhard, 2006):

Kinematic viscosity, vf= 2.474 × $10^{-7}$$m^2$/s

Prandtl number, Pr_f= 4.373

Thermal conductivity, k_f= 0.0988 W/mK

The steps followed involved:

i. Calculating the refrigerant velocity in evaporator pipe.
ii. Calculating Reynolds number ReD using Eqn. 1:

$$ReD = \frac{Vdi}{Vf} = 396.12 < 2100 \quad (1)$$

Flow is laminar.

For laminar flow, Nusselt number N_{uD} and friction factor f were calculated using appropriate correlations.

Inside convective heat transfer coefficient h_i was calculated using Eqn. 2:

$$h_i = \frac{NuD \times kf}{di} \quad (2)$$

Finally, evaporator pipe length L was calculated using the heat transfer equation presented in Eqn. 3:

$$Q = \frac{\pi diLhihoΔT}{hi+ho} \quad (3)$$

Thereafter, all values were Substituted to solve for L

b. Length of Condenser Pipe

Given:

Heat transfer rate, Q_{cond}= 21.09W

Outer diameter, do= 0.008m

Inner diameter, di=0.007m

Outside heat transfer coefficient, h_o= 9.37 W/m^2K

Temperature difference, ΔT = 50 – 34 = 16 K

Thermal conductivity of copper at 50°C, k_{cu} = 399.16W/mK

Thermo-physical properties of saturated vapor R134a at 50°C (from Lienhard & Lienhard, 2006):

Density, ρg = 67.46 kg/m^3

Dynamic viscosity, μg =13.13 × 10^{-6} kg/m·s

Prandtl number, $Pr_g = 0.9834$

Thermal conductivity, $k_g = 0.01681$ W/mK

The steps followed involved:

i. Calculating the refrigerant velocity in condenser pipe.
ii. Calculating Reynolds number R_{eD} using Eqn. 1:

ReD = 11149.14 > 2100

Flow is turbulent.

For turbulent flow, use the Dittus-Boelter equation for N_{uD} and the Blasius correlation for friction factor f

Inside convective heat transfer coefficient was calculated using Eqn. 4.

$$h_i = \frac{NuD \times kg}{di} \qquad (4)$$

Thereafter, condenser pipe length L was calculated using the heat transfer equation similar to evaporator.

(c) Length of Capillary Tube

Given:

Pressure drop $P=1.6389\times10^5$ N/m^2

Initial pressure $P_1=13.19\times10^5$ N/m^2

Velocity $\nu=0.3$ m/s

Friction factor f=0.03

Hydraulic mean depth $D_h = \frac{0.00081}{4} = 2\times10^{-4}$ m

Specific gas constant R=81 J/kgK (from R134a properties via interpolation)

Using the pressure drop and flow relations, the length of the capillary tube *L* is calculated as;

L=1.66m

These calculations relied on thermos-physical properties of R134a obtained from Lienhard and Lienhard (2006) and verified refrigerant property tables

3.0 RESULTS AND DISCUSSION

Based on the parameters observed during the experiments and subsequent calculations, the following results have been obtained, which are presented in a comparative format below.

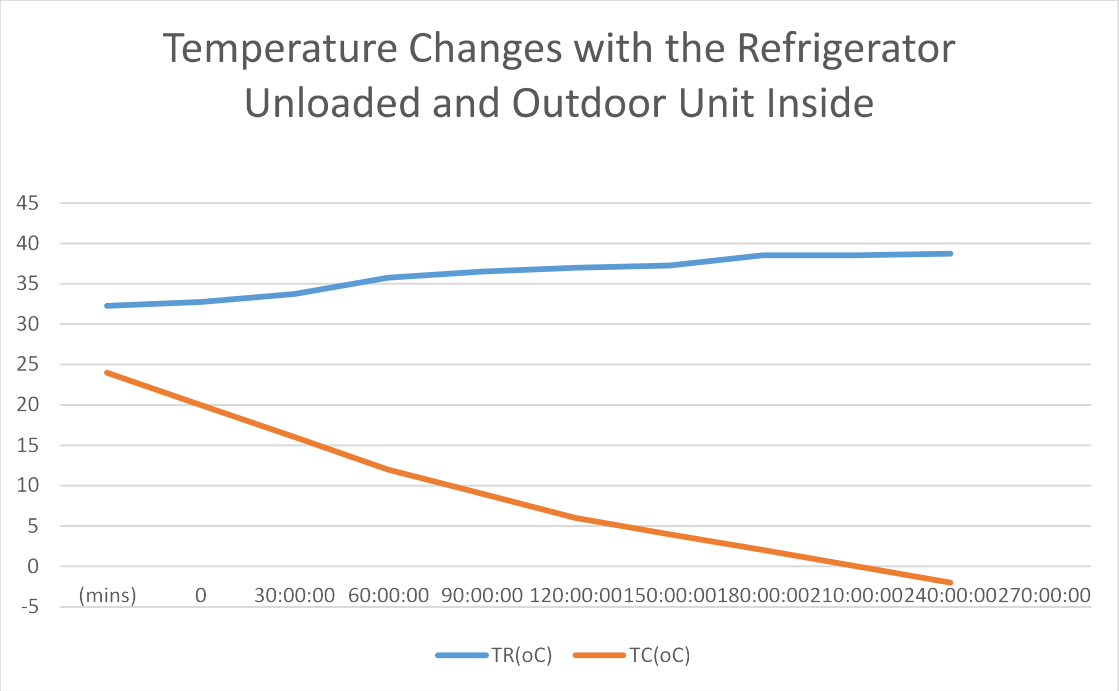


Figure 6: Temperature Changes with the refrigerator unloaded and outdoor unit inside

The results presented in Figure 6 showed over 270 minutes, with the refrigerator unloaded and its outdoor unit inside, the plot reveals a performance dynamic where the refrigerator compartment temperature (TC) dramatically decreases from approximately 25°C to below 0°C, demonstrating cooling, while the surrounding ambient temperature (TR) rises from about 34°C to 39°C, likely due to the confined heat emitted by the outdoor unit.

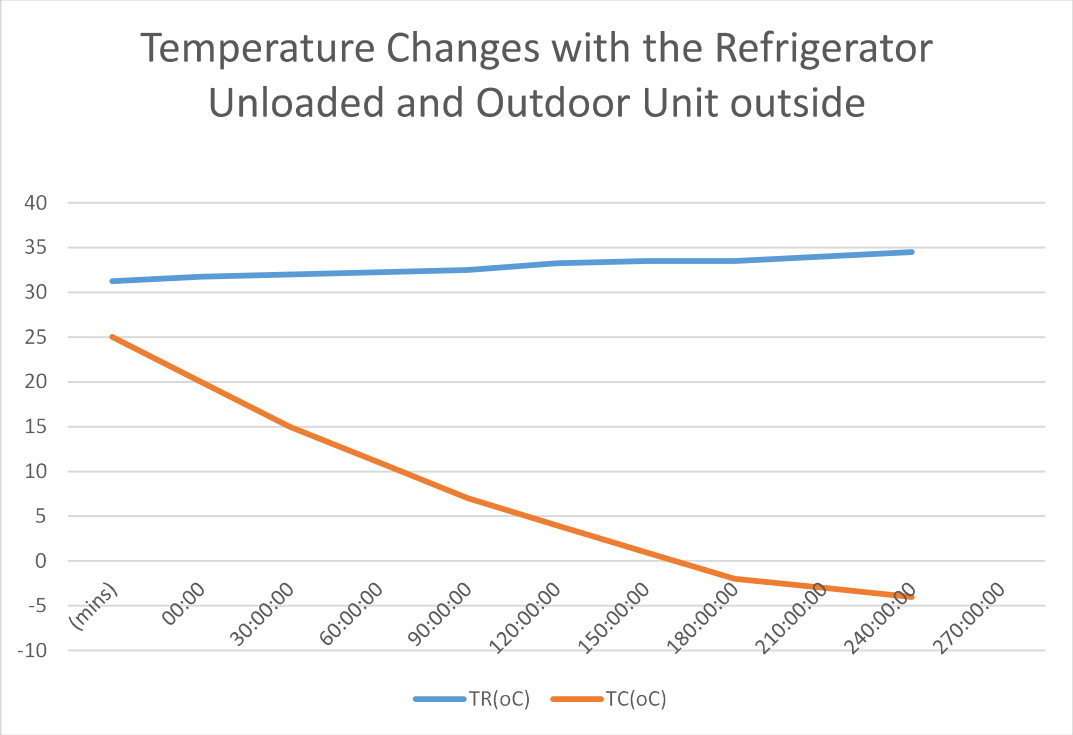


Figure 7: Temperature Changes with the refrigerator unloaded and outdoor unit outside

The results presented in Figure 6 showed over 270 minutes with the refrigerator unloaded and the outdoor unit inside, the Figure 6 shows that the temperature inside the refrigerator (TC) decreases from 25°C to -3°C while the surrounding temperature (TR) increases from 32°C to 39°C.

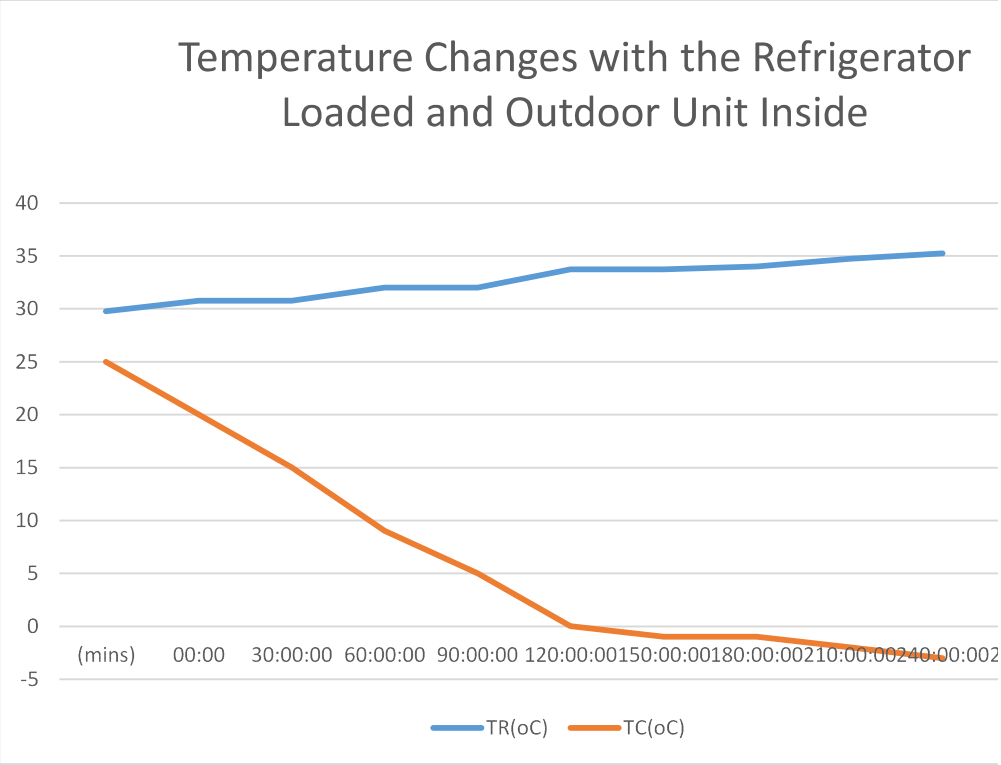


Figure 8: Temperature Changes with the refrigerator loaded and outdoor unit inside

Figure 8 revealed that the temperature inside the refrigerator (TR) increases from approximately 30°C to 35°C over 270 minutes while the temperature of the compressor (TC) decreases from 25°C to 0°C over 150 minutes and then remains constant.

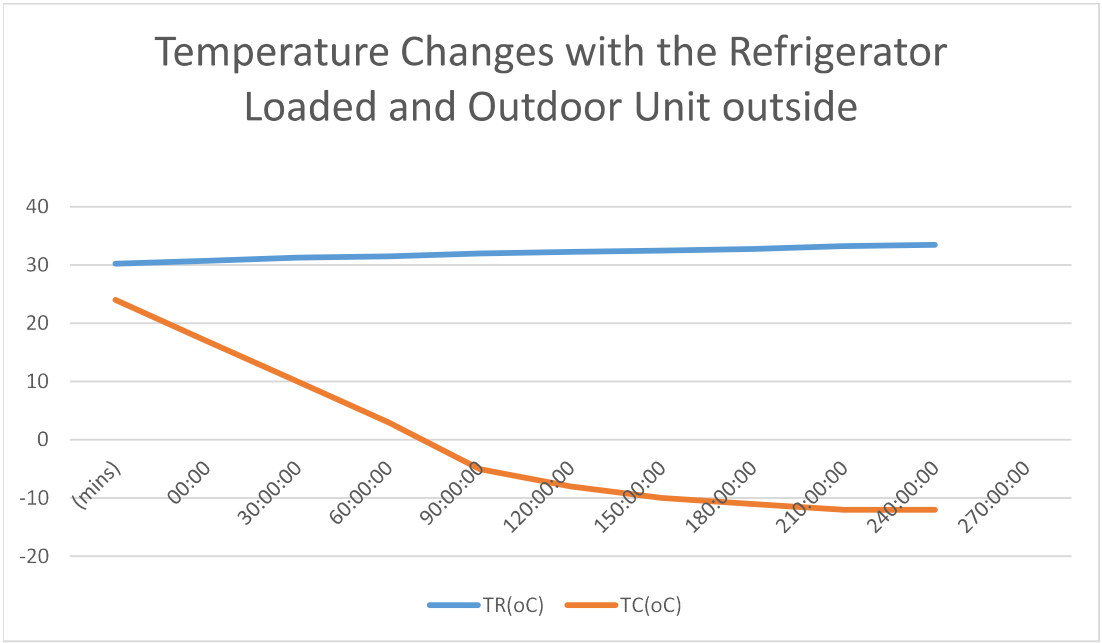


Figure: 9

Figure 9: Temperature Changes with the refrigerator loaded and outdoor unit outside

Figure 9 illustrates that as time increases, the temperature of the refrigerator (TR) increases slightly from 30 to 33 degrees Celsius, while the temperature of the cooling unit (TC) drops significantly from 24 to -17 degrees Celsius over approximately 270 minutes.

5.0 CONCLUSION

Upon completion of the experiments, several key conclusions were drawn. It was observed that the average room temperature (TR) was higher when the outdoor unit was located inside the room compared to when it was outside. Specifically, at 270 minutes, the average room temperature reached 38.75°C with the outdoor unit inside the room while the system was loaded, compared to 34.5°C when the system was unloaded under the same conditions. Similarly, at the 270-minute mark, TR was 35.25°C with the outdoor unit inside the room, whereas it was lower at 33.50°C when the outdoor unit was placed outside the room.

Furthermore, the cooling effect was noticeably more effective when the outdoor unit was positioned outside the room. At 270 minutes, the evaporator temperature was approximately -2°C and -3°C for the unloaded and loaded systems respectively when the outdoor unit was inside the room. In contrast, when the outdoor unit was outside the room, the evaporator temperature dropped further to about -4°C for the unloaded system and significantly lower to -12°C for the loaded system.

These findings clearly indicate that placing the outdoor unit outside the room enhances cooling performance and helps maintain a lower average room temperature, especially when the refrigerator is loaded.

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