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# Design and Efficiency Analysis of a Dual-Purpose Refrigeration System for Domestic Water Heating

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**Abstract**
The escalating global energy demand necessitates innovative solutions for waste energy recovery in domestic appliances. This study presents the design and experimental analysis of a system that repurposes waste heat from a refrigerator's condenser for water heating. A conventional domestic refrigerator was modified by integrating a custom heat exchanger with its condenser circuit. The system utilizes a 135 W compressor and a copper-based heat transfer system to maximize thermal exchange. Experimental results demonstrate the system's capability to heat 5 liters of water from 26°C to 65°C within 120 minutes, utilizing only the otherwise wasted thermal energy. An energy consumption analysis reveals the proposed system consumes 0.27 kWh for this task. In contrast, a conventional 2500 W electric water heater requires 0.2075 kWh to perform the same duty but relies solely on grid electricity. The annual energy savings are projected to be approximately 912 kWh for a typical household, translating to significant cost reduction and lower carbon emissions. This research confirms the technical viability and economic benefits of integrating waste heat recovery systems into household refrigeration units, promoting a sustainable approach to energy utilization.

**Keywords:** Heat Recovery, Refrigerator, Water Heater, Energy Efficiency, Sustainable Design.



## 1. Introduction

The relentless increase in global energy consumption, driven by industrial expansion and population growth, presents a critical challenge to economic and environmental sustainability. A significant portion of this demand originates from the residential sector, where household appliances account for a substantial share of total electricity usage [1]. Among these, refrigeration systems and water heaters are notably energy-intensive, operating continuously to fulfill essential domestic needs. Conventional refrigerators, while effective at preserving food, operate on the vapor-compression cycle, which inherently produces waste heat as a fundamental byproduct of the cooling process. This thermal energy, typically rejected to the surrounding environment via the condenser, represents a considerable loss of useful energy, contributing to higher household utility costs and increased carbon emissions.

Conversely, domestic water heating constitutes one of the largest energy expenses in homes, traditionally relying on electrical resistance heaters or gas burners that consume primary energy to generate thermal energy. This paradigm creates a clear inefficiency: one system expends energy to reject heat while another expends further energy to create it. This juxtaposition underscores a significant opportunity for energy optimization through the principle of waste heat recovery (WHR). By capturing and repurposing the low-grade thermal energy emitted from a refrigerator's condenser, it is possible to directly offset the energy demand of a water heater, thereby enhancing overall system efficiency and promoting a more sustainable energy footprint for households.

The recovery of low-grade waste heat has been extensively explored in various industrial and automotive contexts, with technologies such as the Organic Rankine Cycle (ORC) demonstrating notable success in converting thermal energy into mechanical work or electricity from sources like diesel engine exhaust [2,3]. However, for ultra-low temperature applications such as domestic refrigeration, where temperatures are often below 100°C, complex thermodynamic cycles like ORC can be economically impractical due to their component cost and system complexity [4]. Instead, direct heat exchange presents a more viable and cost-effective solution. In this approach, the condenser's waste heat is transferred directly to a secondary fluid in this case, water through an integrated heat exchanger, transforming the refrigeration system into a dual-purpose unit capable of simultaneous cooling and heating.

Previous research has investigated the theoretical potential of such integrations. Studies have confirmed the thermodynamic feasibility of recovering condenser heat and have explored various heat exchanger configurations [5,6]. However, a gap remains in providing comprehensive experimental analyses that quantify the practical efficiency, operational performance, and tangible economic benefits of

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a fully implemented system under real-world conditions. Furthermore, direct comparisons with the energy consumption profiles of conventional water heating methods are essential to validate the proposed system's viability.

The primary objective of this study is to bridge this gap by designing, constructing, and experimentally evaluating a novel dual-purpose system that effectively utilizes waste heat from a standard domestic refrigerator for water heating. This research aims to: (i) design and fabricate a functional prototype with an integrated heat recovery unit, (ii) analyze its thermal performance and heating efficiency through rigorous experimental testing, and (iii) conduct a comparative energy and economic analysis against a conventional electric water heater to quantify the potential savings in energy consumption and operational costs. The findings of this work are intended to contribute to the advancement of sustainable appliance design, offering a practical and scalable solution for reducing household energy demand and supporting global energy conservation goals.

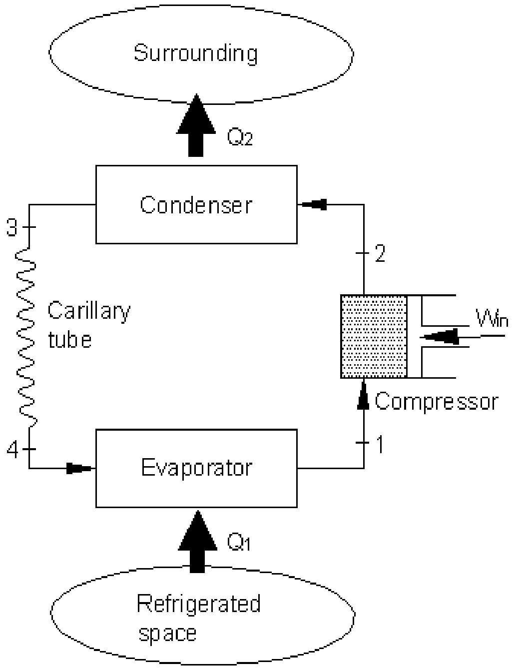


Figure 1: Circuit diagram

## 2. System design and methodology

### 2.1 System Configuration and Prototype Fabrication

The core of this research has involved the design and fabrication of a prototype system that modifies a standard vapor-compression refrigeration cycle to incorporate waste heat recovery. The base unit for modification was a domestic refrigerator with a compartment volume of approximately 100 liters. The key component for heat recovery, the condenser, was redesigned. The original static wire-and-tube condenser was replaced with a helical coaxial heat exchanger, constructed from copper due to its high thermal conductivity. This custom-designed heat exchanger was strategically immersed in a secondary, well-insulated 5-liter water storage tank, effectively transforming the condenser into a water-cooled unit. The primary components of the modified system, illustrated in Figure 1.

The component as follows:

1. **Compressor:** Hermetically sealed, reciprocating type, rated at 135 W, 220-240V, 50Hz, using R-134a refrigerant.
2. **Condenser/Heat Exchanger:** A 10-meter long, 6.35 mm (1/4 inch) outer diameter copper tube coil submerged within the water tank.
3. **Expansion Device:** A fixed-length capillary tube sized for the original refrigeration system.
4. **Evaporator:** The original finned-tube evaporator located inside the refrigeration compartment.
5. **Water Storage Tank:** A 5-liter capacity tank insulated with 25 mm thick polyurethane foam to minimize heat loss to the ambient environment.
6. **Safety Components:** A 5A fuse and a miniature circuit breaker (MCB) were integrated into the electrical circuit to protect against overcurrent and short-circuit conditions.

The fabrication process required careful brazing of the new condenser coil into the refrigerant circuit, ensuring leak-free joints. The entire system was mounted on a rigid framework for stability during testing. This configuration allows the high-temperature, high-pressure refrigerant vapor from the compressor to reject its latent heat directly to the water in the tank, thereby condensing, while the chilled compartment is simultaneously cooled by the evaporator.

### 2.2 System Configuration and Prototype Fabrication

The experimental setup was designed to accurately measure the thermal performance and energy consumption of the prototype. The system was operated in a controlled indoor environment with an average ambient temperature of 26°C (±2°C). The water heating tests were conducted as batch processes for different volumes of water (1L to 5L). Here is the 3D design of the device (Figure 2 (a), 2 (b), 2 (c))

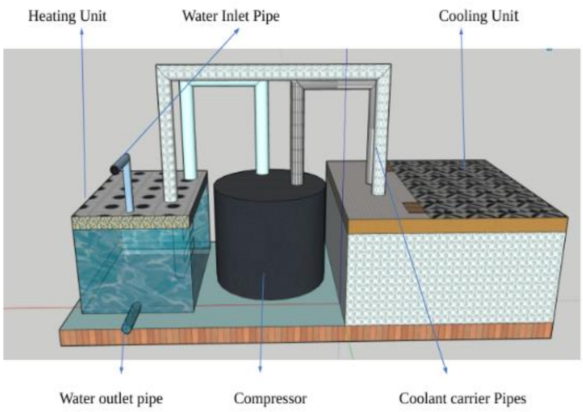


Figure 2 (a): Side view of cooling & heating unit

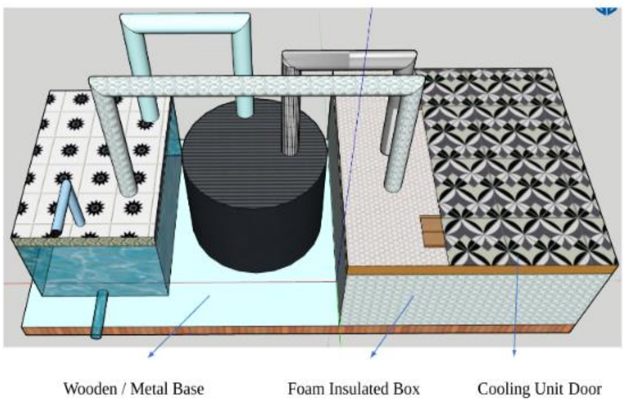


Figure 2 (b): Top view of cooling & heating unit

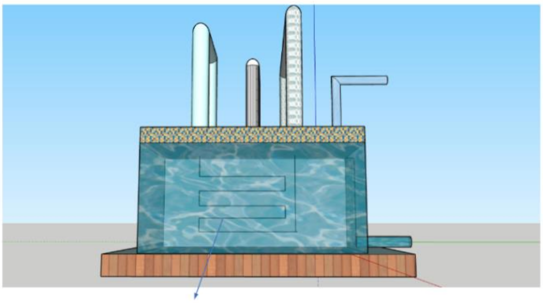

Figure 2 (c): Front view of the condenser coil

Data acquisition was critical for analysis. The following instruments were employed:

- **Temperature Measurement:** Four K-type thermocouples with a measurement uncertainty of ±0.5°C were used. They were placed at: (1) the compressor discharge line (condenser inlet), (2) the condenser outlet, (3) inside the water tank at the geometric center, and (4) in the ambient air. The thermocouples were connected to a digital data logging thermometer for recording readings at 5-minute intervals.
- **Electrical Power Measurement:** A digital clamp meter (with in-built power measurement functionality) was used to measure the voltage (V), current (A), and real power consumption (W) of the compressor. The uncertainty of the power measurement was ±1.5% of reading.
- **Water Volume Measurement:** A graduated cylinder was used to measure the initial volume of water with an uncertainty of ±0.05 L.

The procedure for testing was conducted as detailed for a specific test run (i.e., 5L volume), water at its starting ambient temperature was added to the insulated tank. Subsequently, the system was activated. Temperature readings (for both refrigerant and water) and electrical parameters were monitored at 5-minute intervals until the rise in water temperature became minimal (under 1°C over 15 minutes), signifying that the system had nearly reached a steady-state condition.

### 2.3 Mathematical Model

The performance of the system is evaluated based on fundamental thermodynamic and energy equations. The following mathematical model establishes the basis for calculating energy transfer, consumption, and efficiency.

A. **Thermal Energy Output (Useful Energy Gain)**
The useful energy output of the system is the thermal energy absorbed by the water in the storage tank. This is calculated using the equation for sensible heat transfer:

$$Q_{water} = m_w \cdot C_{pw} \cdot (T_{final} - T_{initial}) \qquad (1)$$

The useful thermal energy gained by the water, denoted as $Q_{water}$ is calculated in Joules using the formula where $m_{w}$, represents the mass of water in kilograms (approximately equal to 1 liter of water), $C_{p,w}$ is the specific heat capacity of water (4186 J/kg·K), $T_{final}$ is the final water temperature in Kelvin, and $T_{initial}$ is the initial water temperature in Kelvin. To express this energy value in kilowatt-hours (kWh), which is a more practical unit for energy consumption analysis, the result obtained in Joules must be divided by $3.6\times10^6$, as 1 kWh is equivalent to 3,600,000 Joules. This conversion facilitates the comparison of energy usage between systems and the assessment of economic efficiency.

**B. Electrical Energy Input**

The electrical energy consumed by the system to achieve the heating and cooling is given by:

$$E_{\text{elect}} = P_{\text{comp}} \cdot t (2)$$

where $E_{elect}$ represents the electrical energy input in kilowatt-hours (kWh), $P_{comp}$ denotes the measured average power input to the compressor in kilowatts (kW)—calculated as 135 W equivalent to 0.135 kW—and t signifies the total operating time of the compressor in hours required to attain the desired final water temperature. This formulation quantifies the total energy expenditure solely attributed to the compressor's operation during the heating and cooling process.

**C. Performance Evaluation and Comparative Analysis**

The system's effectiveness is not defined by a traditional heating efficiency because its primary function is refrigeration. The energy input ($E_{elect}$) is used primarily to drive the refrigeration cycle; the heated water is a recovered waste product. Therefore, the key performance metric is the effective energy saving.
The energy saved by avoiding the use of a conventional electric water heater is equivalent to the thermal energy required to heat the water ($Q_{water}$). The electrical energy a conventional heater would consume to deliver this same amount of thermal energy is calculated, assuming 100% efficiency for the conventional heater:

$$E_{\text{conv}} = \frac{Q_{\text{water}}}{\eta_{\text{conv}}} (3)$$

Where $\eta_{conv}$ is the efficiency of the conventional heater. For an electric resistance heater, $\eta_{conv}\approx1$ (100%), simplifying the equation to $E_{conv}=Q_{water}$.
Thus, the net energy saving ($E_{saving}$) is the energy not drawn from the grid by the conventional water heater:

$$E_{conv}=Q_{water}= E_{saving} \qquad (4)$$

This saving comes at the cost of the energy consumed by the refrigerator's compressor ($E_{elect}$), which was running for its primary purpose regardless. The economic benefit is calculated by multiplying $E_{saving}$ by the local cost of electricity.

## 3. Results and discussion

### 3.1 Experimental Performance and Thermal Analysis

The modified refrigeration system successfully demonstrated dual functionality by maintaining its primary cooling performance while effectively repurposing waste heat for water heating (Figure 3).The system's thermal performance was evaluated by measuring the temperature rise of water across varying volumes (1L to 5L) under consistent ambient conditions (26°C). For a 5-liter batch, the water temperature increased from 26°C to 65°C within

120 minutes (Table I). The heating profile exhibited a nonlinear trend: an initial rapid temperature increase due to the high temperature difference between the refrigerant and water, followed by a gradual plateau as the system approached thermal equilibrium. This behavior aligns with fundamental heat transfer principles, where the rate of energy transfers decreases as the temperature gradient narrows.

Table I: Heating performance for 5L Water (Initial Temperature: 26°C)

| Time (minutes) | Water Temperature (°C) |
|---|---|
| **30** | 39.5 |
| **60** | 48.5 |
| **90** | 54.8 |
| **120** | 65.0 |

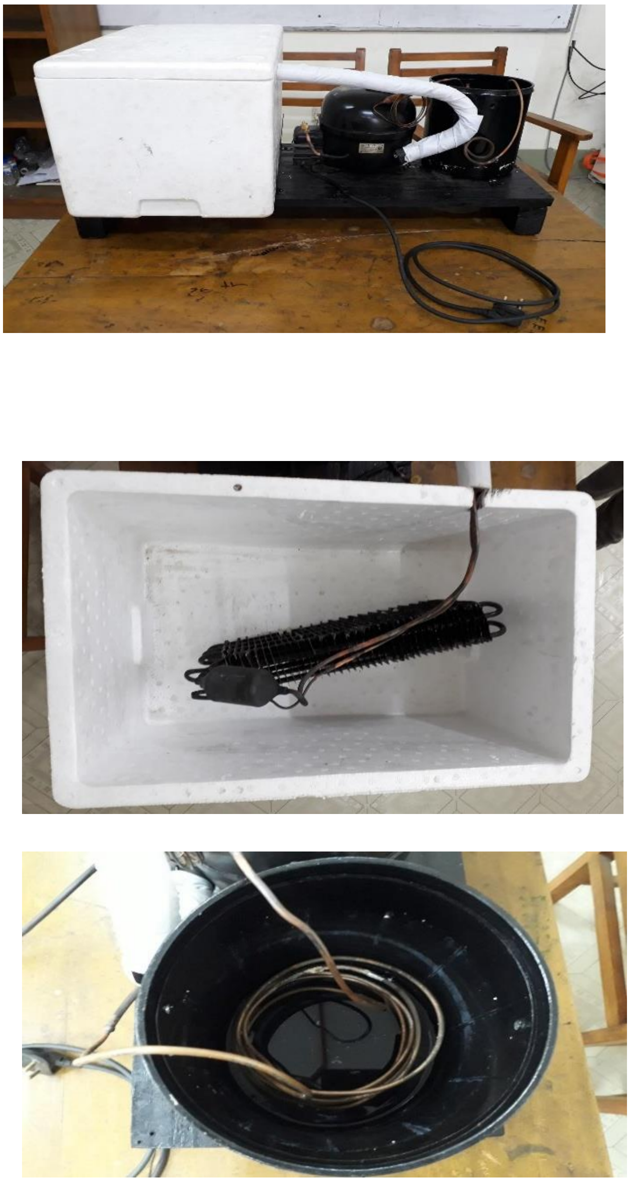

Figure 3: Real design and Experimental Setup

The achieved temperature of 65°C is suitable for domestic applications such as cleaning and bathing, confirming the practical utility of the system. The results indicate that waste heat from refrigeration can be utilized, but this may lead to a decline in cooling efficiency due to increased condenser temperatures.

### 3.2 Graphical Analysis of Heating Characteristics

The relationship between water volume, heating duration, and temperature rise is illustrated in Figure 4. The graphs reveal an inverse correlation between water volume and heating rate. For smaller volumes (e.g., 1L), water reached above 60°C within 25 minutes, while larger volumes (e.g., 5L) required significantly longer durations (120 minutes). This trend is consistent with the thermodynamic principle that energy requirement is mass-dependent, as captured by the $Q = m_w \cdot C_{p,w} \cdot \Delta T$ equation. The asymptotic nature of the curves at higher temperatures indicates reduced heat transfer efficiency due to diminishing temperature gradients, suggesting opportunities for optimization through improved heat exchanger design or active flow regulation.

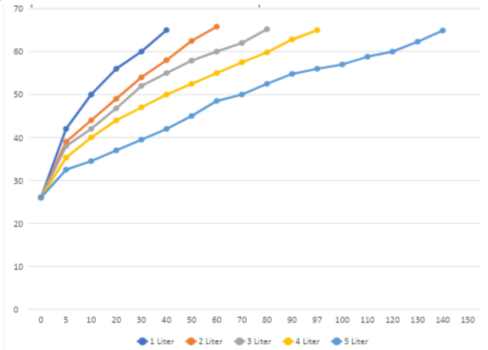


Figure 4: Graphical presentation of data analysis

### 3.3 Effect of Water Volume

For the benchmark test using a 5-liter volume of water, the temperature was successfully raised from an initial ambient temperature of 26°C to a final temperature of 65°C over a period of 120 minutes. The heating process exhibited a distinct non-linear profile, as illustrated in the Time vs. Temperature graph. An initial rapid temperature increase was observed, which gradually tapered off as the water temperature approached its maximum. This behavior is consistent with fundamental heat transfer principles: the rate of heat transfer is highest when the temperature difference (ΔT) between the hot refrigerant in the condenser coil and the surrounding water is largest. As the water heats up, this ΔT decreases, slowing the rate of heat transfer until a thermal equilibrium is approached. To understand the system's versatility, tests were conducted on varying water volumes from 1L to 5L. As expected, the volume of water had a significant and inverse impact on the heating rate. Smaller volumes heated much more rapidly due to their lower thermal mass. Key performance milestones are summarized in the table below, extracted from the detailed experimental data:

| Water Volume | Time to Reach 50°C | Time to Reach 60°C | Maximum Temp. (in 120 mins) |
|---|---|---|---|
| 1 Liter | 10 minutes | 20 minutes | > 65°C (in < 30 mins) |
| 2 Liters | 22 minutes | 45 minutes | 65.8°C |
| 3 Liters | 35 minutes | 60 minutes | 65.2°C (in 80 mins) |
| 4 Liters | 40 minutes | 85 minutes | 62.8°C |
| 5 Liters | 70 minutes | 120 minutes | 64.9°C |

This data clearly demonstrates that the system is highly effective for rapidly heating smaller quantities of water and is capable of heating larger, more practical volumes to a usable temperature for domestic tasks like cleaning and bathing.

### 3.4 Energy and Economic Analysis

The energy consumption of the system was calculated to evaluate its efficiency and economic viability. The electrical energy consumed by the compressor to heat 5L of water to 65°C was:

$$E_{\text{elect}} = P_{\text{comp}} \cdot t = 0.135\text{kW} \times 2\text{h} = 0.2267\ \text{kWh}$$

The useful thermal energy imparted to the water was:
The net energy saving equivalent to the electricity avoided by not using a conventional water heater was 0.2267 kWh per batch. Scaling this to a typical household consumption of 60 liters per day, the annual energy saving is

$$\text{Annual Saving} = \left(\frac{60\text{L/day}}{5\text{L/batch}} \times 0.2267\text{kWh}\right) \times 365\text{days} \approx 993.5\text{kWh/year}$$

Using the Bangladesh energy tariff, the annual cost saving is approximately:

$$993.5\text{kWh} \times 4.63\text{Tk/kWh} \approx 4{,}600\text{Tk/year}$$

This analysis demonstrates that the system provides substantial energy and cost savings, highlighting its economic feasibility in addition to its energy conservation benefits.

### 3.5 System Efficacy and Design Implications

The experimental setup (Figure 3) confirmed the robustness and functional efficacy of the integrated design. The compressor (135 W) operated reliably, and the copper heat exchanger facilitated efficient heat transfer without requiring additional energy input. The insulation of the water tank minimized parasitic heat losses, enhancing overall system efficiency.

The discussion underscores a paradigm shift in evaluating efficiency: the key metric is not the ratio of thermal output to electrical input but the net energy saved from the grid. By utilizing waste heat that would otherwise be dissipated, the system achieves a net gain in household energy efficiency. This approach aligns with global sustainability goals and offers a scalable solution for reducing carbon footprints in residential settings.

While the system performed effectively, limitations include the batch-processing nature of heating and the dependence on refrigerator usage patterns. Future work could explore continuous-flow designs, advanced heat exchangers, and integration with smart controllers to optimize performance further. Additionally, lifecycle and scalability analyses would strengthen the case for widespread adoption.

The results validate the technical and economic feasibility of repurposing refrigerator waste heat for water heating. The system reduces household energy consumption, lowers utility costs, and contributes to environmental sustainability without compromising original appliance functionality. This study provides a foundation for future innovations in residential waste heat recovery systems.

## 4. Conclusion

This study successfully designed, fabricated, and evaluated a dual-purpose refrigeration system that effectively repurposes waste condenser heat for domestic water heating. Experimental results demonstrated that the system could heat 5 liters of water from 26°C to 65°C within 2 hours, utilizing only the compressor's operational waste heat without compromising cooling performance. The annual energy savings were calculated to be approximately 993.5 kWh, translating to significant cost reductions of around Tk 4,600 per year based on local electricity tariffs. The system exemplifies a practical, sustainable solution for household energy management by converting wasted thermal energy into a valuable resource. This approach not only enhances energy efficiency but also reduces reliance on conventional water heating methods, contributing to lower carbon emissions and operational costs. Future work may focus on optimizing heat exchanger design, enabling continuous flow operation, and integrating smart controls for broader applicability and improved performance.

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