Experimental Evaluation of a Compact Ice-Bath Cooling Apparatus for Rapid Temperature Reduction

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Abstract. This study presents the design, thermal modelling, and experimental evaluation of a compact ice-bath cooling apparatus intended to accelerate heat extraction for laboratory and beverage-cooling applications. The system applies conductive and convective cooling principles to reduce fluid temperature through a controlled ice-water interface. A detailed review of refrigeration and thermoelectric cooling concepts supports the design framework, while CAD modelling and component selection ensure thermal stability and structural efficiency. Experimental testing was conducted using four trials to measure temperature reduction over time and evaluate cooling performance under varying conditions. Results show that the proposed system achieves consistent temperature drops, validating its potential for small-scale cold-chain, laboratory, and consumer cooling needs. The work contributes a practical, low-energy cooling solution suitable for applications requiring rapid and localized heat removal.

Keywords: Ice-bath cooling, Thermal analysis, Heat transfer, Rapid cooling system, Experimental evaluation, Compact cooling apparatus.

1 Introduction

Rapid temperature reduction is essential across various laboratory, industrial, and consumer applications, including beverage cooling, chemical stabilization, biological sample preparation, and thermal conditioning of materials. Traditional refrigeration systems rely on vapor-compression cycles, which, although effective, often require substantial energy input, bulky components, and long cooling times [1]. Ice-bath cooling offers a simpler and energy-efficient alternative by exploiting thermal gradients between a warm object and a near-freezing medium.

The fundamentals of heat extraction in cooling systems are typically based on conduction, convection, or a combination of both. In vapor-compression systems, heat transfer occurs through refrigerant evaporation and compression cycles. In contrast, ice-bath systems rely on conductive heat transfer through direct contact with cold water and ice, enabling rapid thermal exchange without the complexity of mechanical refrigeration [2].

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With the rising need for compact cooling devices in laboratories, DIY research setups, and low-energy applications, there is significant motivation to design efficient cooling systems that do not rely on electrical compressors. This study aims to evaluate a prototype ice-bath cooling apparatus developed by students as part of a diploma engineering project. The work includes theoretical thermal analysis, CAD-based structural design, and experimental testing of cooling performance.

2 Literature Review

2.1 Fundamentals of Heat Extraction

Heat removal from an object can occur through conduction, convection, or radiation, with conduction and convection being predominant in cooling systems [3], [4]. In ice-bath systems, the solid–liquid transition of ice provides a large thermal sink, enabling effective heat absorption. Figure 1 presents the basic concept of an ice-bath cooling interface.

Fig. 1. Ice bath heat extraction concept.

The enthalpy of fusion of ice plays a critical role in maintaining near-constant temperatures around 0°C until the ice fully melts, allowing stable cooling conditions [5].

2.2 Refrigeration and Alternative Cooling Technologies

Traditional refrigeration systems use refrigerants circulating through evaporators and condensers (Figure 1), but alternative low-power solutions have gained traction [6]. Thermoelectric cooling, based on the Peltier effect, offers compact cooling without refrigerants, though with lower efficiency compared to vapor-compression systems [7], [8].

Such systems are useful for precise temperature control in electronics, portable cooling devices, and experimental setups where space is limited.

2.3 Components of Compact Cooling Systems

Compact cooling devices typically incorporate insulated containers, heat exchangers, cooling media, and circulation systems to enhance thermal transfer. These components contribute to effective heat transfer by increasing surface contact area, improving circulation, and maintaining stable thermal gradients.

2.4 Problem Statement and Need for a Compact Cooling Solution

The original student project identifies the need for a cooling apparatus that:

- Reduces temperature rapidly
- Is portable and simple to operate
- Requires minimal energy input
- Is suitable for cooling beverages and laboratory samples

Existing cooling solutions are often bulky, slow, or dependent on external power sources [9]. Ice-bath cooling offers an effective, low-cost solution that can be optimized through appropriate design and material selection [10].

2.5 Summary of Literature Gaps

From the reviewed studies, the following gaps were identified:

- Limited experimental evaluation of simple, portable ice-bath cooling systems
- Insufficient integration of CAD modelling with thermal performance testing
- Need for optimized container geometry to improve cooling efficiency
- Few studies comparing multi-trial cooling performance across varying conditions

This project addresses these gaps through modelling, design, and physical testing of a compact cooling system.

3 Methodology

The methodology adopted for the development of the compact ice-bath cooling apparatus consisted of three interconnected stages: (1) system design and thermal estimation, (2) CAD modelling and component preparation, and (3) experimental evaluation through multiple temperature-drop trials.

3.1 System Design Approach

The cooling apparatus was designed to maximize conductive heat transfer between the test fluid container and the surrounding ice-water mixture. The core objectives guiding the system design included:

- Enhancing surface contact area between the container and cold medium
- Ensuring structural insulation to minimize heat gain from the surroundings

- Maintaining a stable mixture of ice and water to optimize cooling rates

The design focused on optimizing container geometry, insulation thickness, and the interface between the cooling chamber and the fluid container to achieve efficient thermal exchange.

3.2 CAD Modelling of the Cooling Apparatus

A detailed CAD model was developed to visualize assembly layout, verify internal spacing, and ensure ergonomic placement of the cooling chamber. The CAD model, shown in Figure 2, informed key design decisions such as:

- Internal cavity depth
- Diameter matching between sample container and ice chamber
- Placement of insulation layer
- Wall thickness for thermal stability

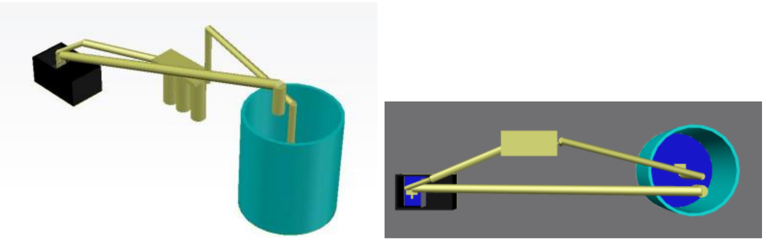

Fig. 2. CAD model of the compact cooling apparatus.

3.3 Experimental Design and Procedure

To evaluate system performance, four experimental trials were conducted using identical volumes of fluid. In each trial:

1. The apparatus was filled with a predetermined amount of ice and water.
2. A container filled with room-temperature liquid was placed inside the cooling chamber.
3. Temperature readings were taken at fixed time intervals.
4. Trials were repeated under the same conditions to ensure result reliability.

Temperature measurements were taken using a calibrated thermometer, and data were tabulated and plotted for analysis.

3.4 Thermal Calculation Framework

Thermal performance analysis was based on the principles of conduction and convection. Key equations included:

- Fourier's law for conductive heat transfer

$$Q = kA\frac{\Delta T}{d} \quad (1)$$

- Newton's law of cooling for convective exchange

$$Q = hA(T_s - T_\infty) \quad (2)$$

The enthalpy of fusion of ice was used to estimate the cooling capacity, assuming a constant 0°C cooling medium until complete melting [7].

4 Results and Discussion

4.1 Cooling Performance Overview

Across all four trials, the cooling apparatus demonstrated consistent temperature reduction over time. The overall trend indicated a rapid drop in the first several minutes, followed by a gradual decrease as the temperature approached equilibrium near 0–5°C.

The temperature profile for Trial 1 is shown in Figure 3.

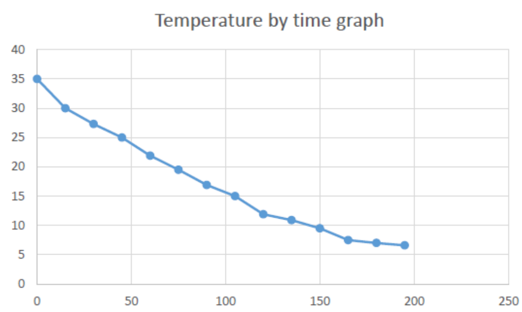

Fig. 3. Temperature drop profile – Trial 1.

Trial 2 demonstrated similar trends, confirming repeatability of performance shown in Figure 4.

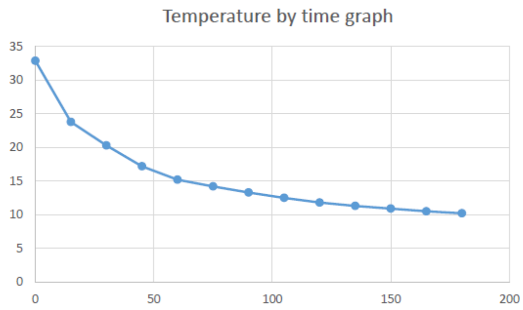

Fig. 4. Temperature drop profile – Trial 2.

4.2 Comparative Analysis of Trials

A comparison of temperature curves, presented in Figure 5, highlights that cooling rates were most rapid during the initial thermal gradient between the warm liquid and the ice-water mixture. This is consistent with classical convective cooling behaviour reported in prior studies [11].

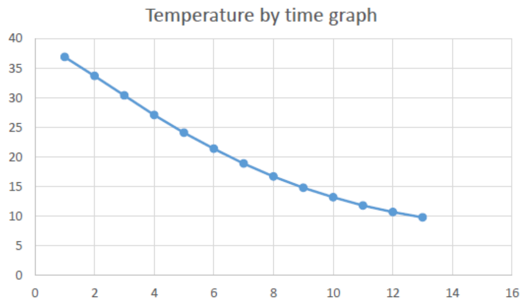

Fig. 5. Comparison of temperature reduction across trials.

Minor differences observed between trials may be attributed to variations in:

- Ice quantity
- Initial water temperature
- Stirring or mixing of the ice-water bath
- Ambient room temperature

These variances are typical in repeated thermal experiments.

4.3 System Efficiency and Observations

The system demonstrated strong efficiency during the early cooling phase due to:

- High temperature gradient
- Direct container contact with ice-water

- Large latent heat absorption capacity

As the ice melted, the system gradually shifted from conductive to convective dominance, yielding slower temperature change rates. The performance indicates that the cooling apparatus is suitable for small-scale applications requiring rapid chilling of liquids, sample preparation, or laboratory cooling needs.

4.4 Limitations

The following limitations were identified:

- Cooling duration depends on ice quantity and melting rate
- Container material significantly influences conductive transfer
- The system does not actively maintain sub-zero temperatures
- Heat leakage through insulation may reduce overall efficiency

Despite these limitations, the apparatus provides an accessible and low-energy solution for rapid temperature reduction.

5 Conclusion

This study successfully designed, modelled, and experimentally validated a compact ice-bath cooling apparatus capable of effectively reducing fluid temperature within short time intervals. A combination of thermal analysis, CAD modelling, and experimental trials demonstrated that the system could provide consistent and repeatable cooling performance using simple and low-cost materials.

Key findings include:

- Rapid cooling achieved during the initial high-temperature gradient
- Consistent cooling patterns across four trials
- Effective use of ice's latent heat for temperature stabilization
- Suitability for beverage cooling, laboratory use, and small-scale thermal conditioning

Future improvements may focus on optimizing insulation, incorporating mechanical mixing, and exploring hybrid cooling mechanisms [12].

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