

The Effect of Water Mass on Freezing Time Using a ½ HP Outdoor Air Conditioner Unit

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DOI: 10.64823/ijter.2604021

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Abstract: The growing demand for ice production in tropical regions necessitates the development of efficient and cost-effective refrigeration systems. This study examines the effect of water mass variation (5 kg, 10 kg, and 15 kg) on the performance of an ice-making machine utilizing an outdoor air conditioning unit (½ PK). The system operates based on the Vapor-Compression Refrigeration Cycle, employing a serpentine evaporator immersed in a 20% saline solution. The experimental results indicate that freezing time increases proportionally with water mass, reaching 2.5 hours for 5 kg, 3.5 hours for 10 kg, and 5 hours for 15 kg. Heat transfer analysis shows that although the total thermal load rises with increasing mass, the system gradually approaches its cooling capacity limit, leading to reduced performance improvement at higher loads. Statistical evaluation using error bar analysis further confirms significant differences between lower and higher mass variations. From an economic perspective, the findings demonstrate that on-site ice production is considerably more cost-effective than purchasing ice, with unit costs decreasing as production volume increases. However, a trade-off emerges between cost efficiency and processing time. Therefore, optimizing the performance of ice-making systems requires a balanced consideration of thermal efficiency, system capacity, and economic viability.

Index Terms: Ice-making machine, Water mass variation, Freezing time, Heat transfer, Vapor-Compression Refrigeration Cycle, Economic analysis, Refrigeration system

I. INTRODUCTION

The development of technology in Indonesia, particularly in the refrigeration sector, continues to grow in response to increasing public demand for cooling systems. This trend is strongly influenced by Indonesia's tropical climate, which is characterized by relatively high ambient temperatures throughout the year. Consequently, the need for cold food and beverages becomes essential in supporting daily activities. Refrigeration systems play a vital role in maintaining product quality and extending the shelf life of food through temperature reduction processes, which are fundamentally governed by principles of Thermodynamics and Heat Transfer [1-2].

One of the most important applications of refrigeration technology is the ice-making machine. This device is specifically designed to convert water into ice within a relatively short time, offering an efficient, practical, and versatile solution for meeting ice demand across various sectors. Ice plays a crucial role, particularly in the food and beverage industry and fisheries. In the fisheries sector, ice is widely used to preserve the freshness of fish catches, ensuring longer storage life and maintaining product quality. Compared to other cooling methods, ice is considered more economical and accessible, making it a preferred cooling medium in many communities [3].

The advancement of refrigeration technology has been ongoing for decades, with continuous innovations in energy efficiency, system design, and environmentally friendly materials. One of the most widely used systems

in ice-making applications is the Vapor-Compression Refrigeration Cycle, which consists of key components such as a compressor, condenser, expansion device (capillary tube), and evaporator. This system operates by circulating refrigerant to absorb heat from the cooling medium and reject it to the surroundings [4].

Several studies have been conducted to develop and optimize ice-making systems. Jilan et al. [5] designed an ice-making machine using an outdoor air conditioning unit with a 1/5 PK compressor, demonstrating that crystalline ice could be produced within approximately 180 minutes. Similarly, Aldrin and Anggara [6] analyzed the effect of brine concentration and cooling load in a block ice-making system powered by renewable energy and a smart microgrid, showing that pre-cooled brine significantly reduced production time from 52 hours to approximately 20–21.5 hours. Lubis [7] developed a small-scale ice cube machine with a capacity of 1.35 kg and a freezing time of about 2 hours, while Suradita et al. [8] introduced a Bio-PCM-based system capable of producing 215 kg of ice with a cooling capacity of 2.66 kW.

In addition, Nugroho et al. [9] demonstrated that alternative cooling media such as ice packs could achieve lower temperatures and better thermal performance compared to conventional wet ice in fish preservation. Furthermore, Pramudantoro and Sunanto [10] found that increasing salt concentration in brine solutions could significantly reduce cabin temperature and accelerate the freezing process. These studies highlight that system performance is influenced by various parameters, including refrigerant type, brine concentration, and system configuration.

Despite these advancements, the effect of water mass variation on freezing time has not been extensively investigated. In practical applications, especially in small-scale industries and fisheries, the amount of water processed varies depending on demand, which directly affects system performance and efficiency. Therefore, understanding the relationship between water mass and freezing time is crucial for optimizing ice production systems.

Based on this gap, this study aims to analyze the effect of water mass variation (5 kg, 10 kg, and 15 kg) on freezing time using an ice-making machine based on a ½ PK outdoor AC unit. The evaporator is constructed from 1/4-inch copper pipes arranged in a serpentine configuration and placed inside a freezing chamber containing a 20% saline solution. The water is packaged in plastic bags with a mass of 500 grams per unit. This study is expected to provide insights into improving freezing efficiency and reducing production time compared to conventional methods, which typically require up to 24 hours.

II. PROBLEM STATEMENT

Despite the rapid development of refrigeration technology and the widespread use of ice-making machines, several challenges remain in optimizing their performance, particularly in tropical regions such as Indonesia where the demand for ice is consistently high. Although vapor-compression refrigeration systems are widely implemented due to their efficiency and practicality, their performance is influenced by multiple operational parameters, including system configuration, heat transfer characteristics, and working conditions.

Previous studies, such as Jilan et al. [5], have demonstrated the feasibility of utilizing outdoor air conditioning units for ice production, achieving relatively short freezing times. However, these studies primarily focus on system design and general performance, with limited attention given to the influence of water mass on freezing time. In practical applications, especially in small-scale industries and fisheries, the amount of water being frozen varies significantly and directly affects the efficiency and productivity of the ice-making process.

The lack of comprehensive analysis regarding the relationship between water mass and freezing time creates uncertainty in determining optimal operating conditions for ice-making machines. This limitation may lead to inefficient energy use, longer processing times, and reduced system performance. Therefore, it is necessary to investigate how variations in water mass influence the freezing time and overall heat transfer performance of the system.

Based on the above paragraph, some problem statements can be written as: (i) How does the variation in water mass (5 kg, 10 kg, and 15 kg) affect the freezing time in an ice-making machine using a ½ PK outdoor AC system? (ii) What is the relationship between water mass and the heat transfer rate during the freezing process? (iii) What is the optimal water mass to achieve efficient and faster ice production?

III. MOTIVATION

The growing demand for ice production in tropical regions such as Indonesia highlights the need for efficient and affordable cooling technologies. Although ice-making systems based on the Vapor-Compression Refrigeration Cycle have shown promising performance, their operational efficiency is still influenced by varying working conditions. In particular, the effect of water mass on freezing time has not been thoroughly investigated, despite its importance in real-world applications. Therefore, this study aims to address this gap by analyzing how water mass variation affects the freezing performance of an AC-based ice-making system.

IV. OBJECTIVES

General Objective is to investigate the effect of water mass on the freezing performance of an ice-making machine using a ½ PK outdoor AC system, and the specific objectives are:

- To analyze the relationship between water mass (5 kg, 10 kg, and 15 kg) and freezing time.
- To evaluate the heat transfer performance during the freezing process for different water mass variations.
- To determine the optimal water mass that results in the most efficient freezing time.
- To assess the performance of an ice-making system based on the Vapor-Compression Refrigeration Cycle under varying load conditions.

V. HARDWARE AND SOFTWARE REQUIREMENTS

The experimental setup of the ice-making system is based on a modified outdoor air conditioning unit with a capacity of ½ PK. The main hardware components used in this study include:

1. Compressor – Functions to circulate the refrigerant throughout the system.
2. Condenser – Releases heat from the refrigerant to the surrounding environment.
3. Capillary Tube – Acts as an expansion device to reduce refrigerant pressure.
4. Evaporator – Constructed from 1/4-inch copper pipes arranged in a serpentine configuration to enhance heat transfer performance inside the freezing chamber.
5. Outdoor Fan – Assists in heat dissipation at the condenser.
6. Water Pump – Circulates the brine solution to maintain uniform temperature distribution.
7. Cooling Box (Freezing Chamber) – Contains the evaporator and saline solution (20% NaCl).
8. Refrigerant (R-32) – Serves as the working fluid in the refrigeration cycle.
9. Temperature Measurement Devices (Thermocouples/Thermometers) – Used to monitor temperature at various points in the system.
10. Digital Weighing Scale – Used to measure water mass variations (5 kg, 10 kg, and 15 kg).
11. Plastic Packaging – Used to contain water in 500-gram units during the freezing process.

The software tools used in this study support data acquisition, analysis, and documentation includes:

1. Microsoft Excel – Used for data recording, processing, and graphical analysis of freezing time and heat transfer performance.
2. MsWord – Used for typing and processing the paper writing.

VI. METHODOLOGY

A. Experimental Design

This study employs an experimental method to evaluate the performance of an ice-making system under controlled conditions. The primary objective is to investigate the effect of water mass variation on freezing performance. Experiments were conducted by varying the total water mass (5 kg, 10 kg, and 15 kg) while maintaining consistent operating conditions.

B. Variables

The dependent variables measured during the experiment include: (i) the temperature of the saline solution in the cooling chamber, (ii) the temperature of the water during the freezing process, and (iii) the total freezing time. The independent variable is the water mass variation (5 kg, 10 kg, and 15 kg).

C. Experimental Setup

The experimental apparatus consists of a modified refrigeration system based on an outdoor air conditioning unit as described in Figure 1. The main components include a compressor, condenser, capillary tube, evaporator, fan, water pump, and a cooling box acting as the freezing chamber. Refrigerant R-32 is used as the working fluid.

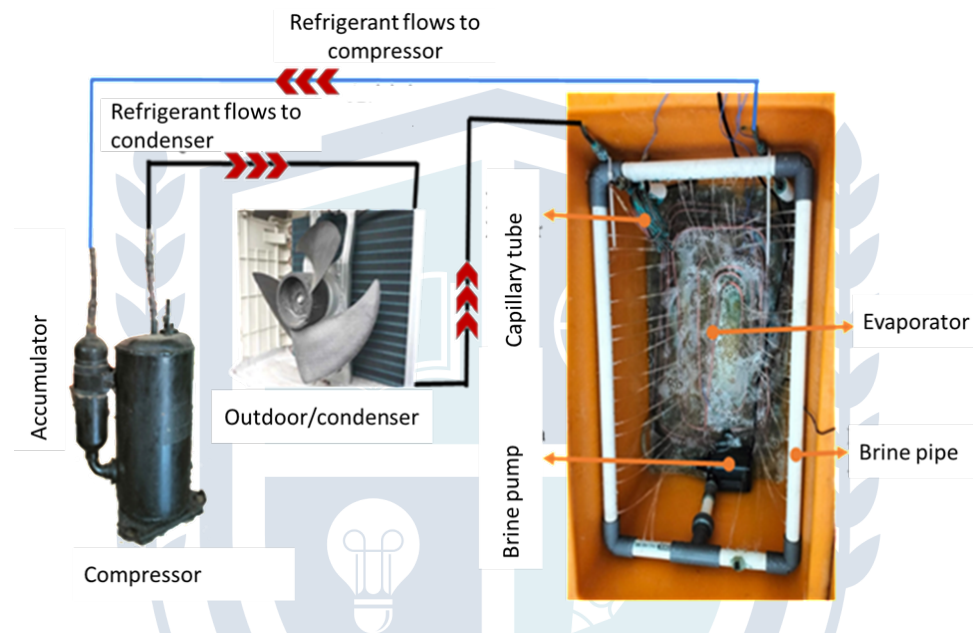


Figure 1. Schematic diagram of the experimental apparatus

The evaporator is installed inside the cooling chamber and operates in conjunction with a circulating saline solution. The brine solution is prepared a 20% concentration (2 kg of NaCl mixed with 8 kg of water) to enhance heat transfer and reduce the freezing point. Water samples are packaged in plastic bags with a mass of 500 g per unit.

The system operates according to the Vapor-Compression Refrigeration Cycle. The compressor increases the refrigerant pressure, followed by heat rejection in the condenser. The refrigerant then expands through the capillary tube before entering the evaporator, where it absorbs heat from the surrounding medium, producing a cooling effect the chamber. The water pump circulates the saline solution to ensure uniform temperature distribution and improve heat transfer efficiency.

D. Experimental Procedure

Prior to testing, the system is assembled and inspected for leakage. Initial measurements of ambient temperature and water temperature are recorded. The packaged water is then placed the cooling chamber according to the specified mass variation. The saline circulation pump and refrigeration system are subsequently activated, and the chamber is sealed.

Data are recorded at 30-minute intervals, including ambient temperature, water temperature, voltage, current, power, power factor, and energy consumption of the compressor and pump. The experiment continues until complete freezing is achieved. The procedure is repeated for each variation of water mass.

E. Data Analysis

The experimental data are analyzed using an error bar percentage approach with a 95% confidence level ($\pm 5\%$ uncertainty). Statistical significance is evaluated based on the overlap of error bars; overlapping intervals indicate no significant difference, while non-overlapping intervals indicate significant variation in the measured parameters.

VII. RESULTS

A. Effect of Water Mass on Freezing Time

The results demonstrate a clear relationship between water mass and freezing time as demonstrated in Figure 2. Increasing the water mass from 5 kg to 15 kg significantly prolongs the freezing duration, from 2.5 hours to 5 hours. This finding is consistent with fundamental heat transfer theory, the total heat load increases proportionally with mass, including both sensible and latent heat components [1-2].

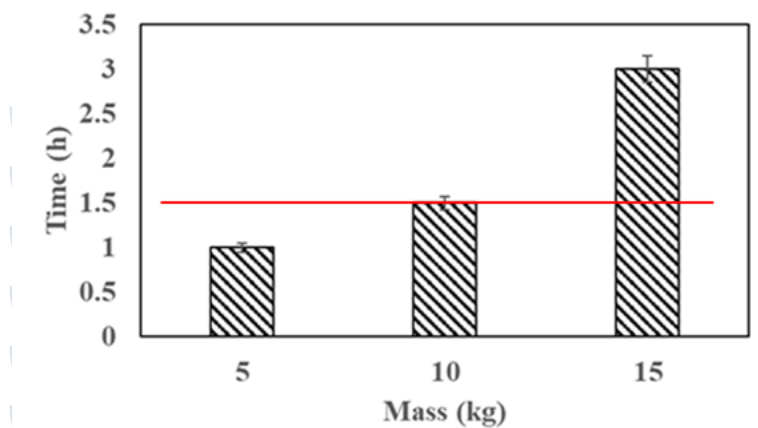


Figure 2. Relationship of water mass and freezing time

From a critical perspective, this result confirms that the system operates under a limited cooling capacity regime. In such systems, increasing the thermal load without increasing cooling capacity inevitably leads to longer freezing times. Similar trends have been reported in recent studies, where freezing time increases nonlinearly with product mass due to internal thermal resistance and limited heat extraction rates (Food Engineering context) [11-12].

Moreover, the increasing time difference (1 hour vs 1.5 hour) suggests that heat transfer efficiency decreases at higher loads. This may be attributed to reduced temperature gradients and increased thermal resistance the system, indicating that the system performance is not fully scalable with load.

B. Total Heat Transfer Rate Behavior

The total heat transfer rate increases with water mass but shows diminishing differences between 10 kg and 15 kg as shown in Figure 3. This indicates that the refrigeration system approaches its maximum cooling capacity, further increases in load do not significantly increase heat transfer rate. This phenomenon aligns with refrigeration system limitations described in [3], where system capacity is constrained by compressor performance and heat exchanger effectiveness. Recent studies also highlight that evaporator performance tends to plateau under high thermal loads due to limited refrigerant flow and heat transfer area as reported by Wang et al. [13]. Critically, this suggests that the system is undersized for higher loads, meaning that increasing water mass beyond a certain threshold does not improve productivity efficiency. Instead, it results in longer processing time without proportional gains in heat transfer.

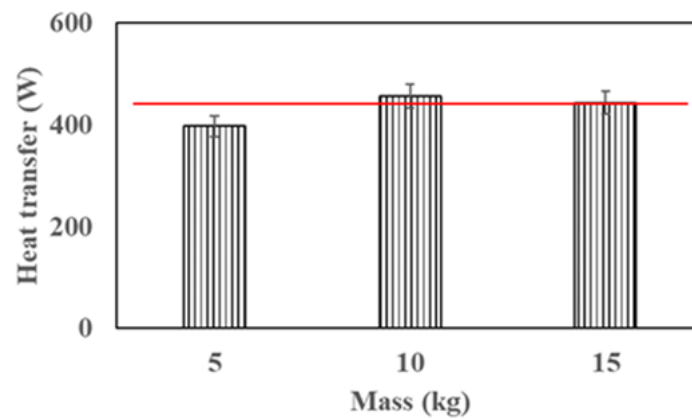


Figure 3. Relationship of water mass and heat transfer rate

C. Heat Transfer from Water (Phase Change Analysis)

The heat transfer rate from the freezing water is strongly influenced by phase change processes, particularly the release of latent heat as shown in Figure 4. During freezing, latent heat dominates the energy removal process, making it a critical factor in determining system performance [2]. A key observation is that differences between 10 kg and 15 kg are not statistically significant, indicating that the system reaches a phase-change-controlled regime. In this regime, heat transfer is limited not by the available energy but by the rate at which latent heat can be removed. Recent research supports this finding, phase change processes often become the bottleneck in freezing systems, particularly when heat transfer coefficients are low or fluid circulation is limited as stated by Zhang et al. [14]. This implies that improving evaporator design or increasing brine circulation could enhance performance more effectively than simply adjusting load.

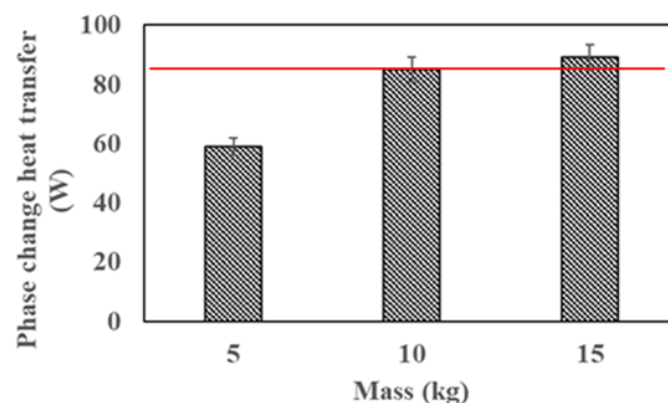


Figure 4. Relationship of water mass and phase change heat transfer rate

D. Heat Transfer from Saline Solution

The results show that the highest heat transfer rate from the saline solution occurs at the lowest water mass (5 kg), and decreases as mass increases as described in Figure 5. This indicates a reduction in effective heat transfer efficiency of the brine system under higher loads. Brine solutions are commonly used to enhance heat transfer by lowering the freezing point and increasing thermal conductivity [1]. However, under higher loads, the circulation effectiveness and temperature uniformity may decrease, reducing overall performance. Recent studies emphasize that brine flow dynamics and mixing intensity significantly affect heat transfer efficiency in freezing systems as explained by Rahman et al. [15]. In this study, the decreasing trend suggests that the pump capacity or flow distribution may not be sufficient to maintain optimal heat transfer at higher water masses.

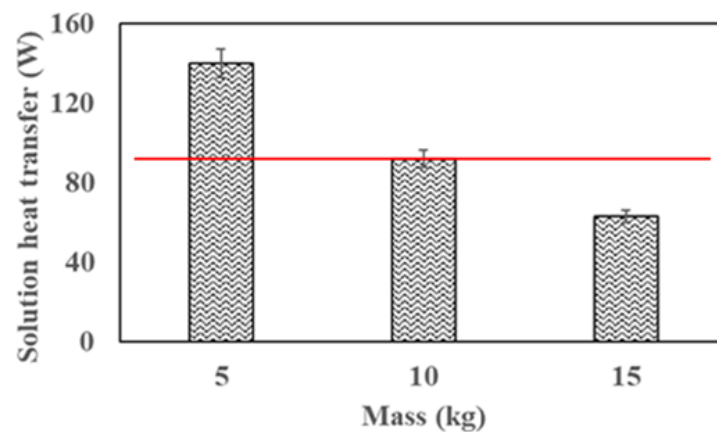


Figure 5. Relationship of water mass and solution heat transfer rate

E. Economic Performance Analysis

The economic analysis reveals that producing ice is significantly more cost-effective than purchasing it, with unit costs decreasing as production volume increases. This trend reflects the principle of economies of scale; fixed operational costs are distributed over larger output quantities [3]. However, a critical observation is that while cost per kilogram decreases, time efficiency decreases simultaneously. This introduces a trade-off between cost and productivity. For real-world applications, especially in fisheries, this trade-off must be carefully balanced depending on operational priorities. Recent techno-economic studies also highlight that optimal system design should consider energy efficiency and production time, rather than focusing solely on cost reduction [16].

Overall, the results demonstrate that water mass significantly affects system performance across thermal, temporal, and economic aspects. However, the system exhibits capacity limitations, increasing load leads to diminishing performance improvements. The key insight from this study is that optimizing an ice-making system should not rely solely on increasing production volume. Instead, improvements in (i) evaporator design, (ii) refrigerant flow rate (iii) brine circulation, (iv) and system capacity, are necessary to achieve better scalability and efficiency. This study contributes to the field by highlighting the importance of load-dependent performance analysis, which is often overlooked in small-scale refrigeration system design.

VIII. CONCLUSION

This study examines the effect of water mass variation (5 kg, 10 kg, and 15 kg) on the performance of an ice-making machine using a vapor-compression refrigeration cycle with a $\frac{1}{2}$ PK outdoor AC unit. The results show that increasing water mass significantly extends freezing time, from 2.5 hours (5 kg) to 5 hours (15 kg), due to higher thermal load. Although total heat transfer increases with mass, the differences between 10 kg and 15 kg are not significant, indicating that the system approaches its cooling capacity limit.

From an economic standpoint, the cost of ice production is lower than market prices. However, a trade-off exists: higher production capacity reduces cost per unit but increases freezing time. Overall, system performance is strongly influenced by load variation, requiring a balance between thermal efficiency and economic performance.

The study also highlights system capacity limitations and integrates thermal analysis, statistical validation (error bars), and economic evaluation. Future improvements should focus on evaporator design, brine circulation enhancement, and increasing system capacity for better scalability.

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