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Design and Fabrication of a Refrigeration System for Garden-Fresh Preservation of Pineapple

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***ABSTRACT*—The preservation of perishable agricultural products is a major challenge in tropical regions, particularly for fruits such as pineapple that are highly sensitive to environmental conditions. This paper presents the design and fabrication of a modified refrigeration system specifically developed for maintaining optimal storage conditions for pineapples. Conventional refrigeration systems often fail to provide the precise temperature and humidity required, leading to quality degradation and economic losses. The proposed system is designed to maintain a temperature and relative humidity, which are considered ideal for pineapple preservation. The system integrates a vapour compression refrigeration cycle using R600a refrigerant, an ultrasonic humidification unit, an optimized airflow distribution mechanism, and a sensor-based control system. The performance of the system was evaluated based on temperature stability, humidity control, airflow uniformity, and energy consumption. Experimental results indicate that the system successfully maintains stable environmental conditions, improves shelf life, and reduces post-harvest losses. The developed model is cost-effective, energy-efficient, and suitable for small-scale agricultural applications.**

KEYWORDS—Pineapple preservation, controlled refrigeration, humidity control, airflow distribution, post-harvest technology, R600a refrigerant, cold storage system

1. INTRODUCTION

Pineapple is one of the most widely cultivated tropical fruits and holds significant economic importance in regions such as Kerala. However, due to its high moisture content and metabolic activity, it is highly perishable and prone to rapid deterioration after harvest. Improper storage conditions result in microbial spoilage, dehydration, enzymatic degradation, and loss of nutritional and sensory quality.

Traditional refrigeration systems are primarily designed for general cooling purposes and do not address the specific requirements of tropical fruits. When pineapples are stored at temperatures below 7°C, they experience chilling injury, which leads to internal browning, tissue breakdown, and loss of flavour. Conversely, storage temperatures above 12°C accelerate respiration and microbial activity, causing rapid spoilage.

In addition to temperature, relative humidity plays a critical role in maintaining fruit quality. Low humidity results in moisture loss and weight reduction, while excessive humidity can promote fungal growth. Therefore, maintaining a controlled environment with optimal temperature, humidity, and airflow is essential.[2],

This study focuses on the design and fabrication of a specialized refrigeration system capable of maintaining these parameters accurately. The system aims to extend shelf life, reduce post-harvest losses, and provide an affordable solution for farmers and small-scale vendors.

2. LITERATURE REVIEW

The preservation of fruits under controlled environmental conditions has been extensively studied in the field of food engineering and refrigeration technology. Research indicates that maintaining a temperature range of 7°C to 12°C and relative humidity of 85–90% is essential for minimizing physiological damage in pineapples.[2]

Studies on vapour compression refrigeration systems show that while they are effective for cooling, they lack precise humidity control. Research on humidity-controlled storage systems highlights that maintaining stable moisture levels significantly reduces dehydration and preserves fruit texture and appearance.[3]

Airflow distribution is another critical factor. Poor airflow leads to uneven cooling, condensation, and localized spoilage. Studies comparing duct designs suggest that circular ducts offer lower friction losses, while rectangular ducts are more practical for compact systems.[9]

Recent advancements in smart systems emphasize the use of sensors and microcontrollers for real-time monitoring and automation. These systems improve efficiency, reduce energy consumption, and maintain consistent storage conditions.

3. PROBLEM IDENTIFICATION

Pineapple farmers in Kerala face significant post-harvest losses due to the lack of proper storage infrastructure. Environmental factors such as heavy rainfall, high temperature, and humidity fluctuations contribute to fruit spoilage.

Additionally, market-related issues such as transportation delays and low demand further increase losses. The absence of controlled storage systems forces farmers to sell produce quickly at lower prices.

Existing refrigeration systems are not optimized for pineapple storage, resulting in either overcooling or insufficient humidity control. Therefore, there is a need for a low-cost, efficient, and portable refrigeration system that can maintain optimal storage conditions.

4. SYSTEM DESIGN AND METHODOLOGY

4.1 DESIGN CONSIDERATIONS

The design of the modified refrigeration system for pineapple preservation was carried out by considering several critical factors that influence the quality, shelf life, and safety of the stored produce. Since pineapples are highly perishable and sensitive to environmental changes, maintaining precise storage conditions was essential.

One of the primary considerations was temperature control. The system was designed to maintain an optimal temperature range between 7°C and 12°C, which is suitable for slowing down metabolic activities and microbial growth without causing chilling injury to the fruit. Maintaining this range ensures extended freshness and reduced spoilage.[2]

Another important factor was relative humidity control. The system was designed to sustain humidity levels between 85% and 95%, which helps in minimizing moisture loss from the pineapples. Adequate humidity prevents shrinkage, weight loss, and surface drying, thereby preserving the texture and appearance of the fruit.[2]

Air circulation and airflow distribution were also carefully considered. Proper airflow ensures uniform temperature and humidity throughout the storage chamber. A controlled airflow rate (designed for approximately 20 Air Changes per Hour (ACH)) helps in preventing localized hotspots and moisture accumulation, which could otherwise promote microbial growth.[1]

The integration of a UV-C sterilization module was another key design consideration. UV-C light is used to reduce microbial contamination in the air and on surfaces within the chamber. This helps in controlling bacterial and fungal growth without the use of chemical preservatives, thereby maintaining the natural quality of the pineapple.[6]

Additionally, energy efficiency was taken into account while selecting components such as the compressor, fan, and humidification system. The system was designed to operate with minimal power consumption while delivering effective cooling and air circulation.

Material selection and structural design were also important considerations. Food-grade and corrosion-resistant materials were chosen for the chamber and trays to ensure hygiene and durability. The internal layout, including tray spacing, was designed to allow proper airflow around each pineapple for uniform preservation.

Finally, ease of operation and maintenance was considered in the design. The system includes simple controls for temperature, humidity, and UV operation, making it user-friendly. Components were arranged to allow easy cleaning, inspection, and replacement.

Overall, these design considerations ensured that the developed refrigeration system provides an optimal environment for pineapple preservation, improving shelf life, maintaining quality, and reducing post-harvest losses.

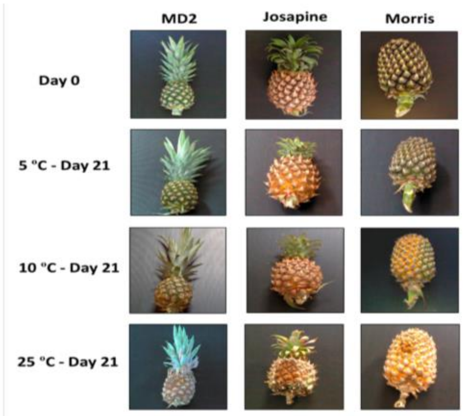


Fig 4.1.1 : Pineapple varieties stored at different temperatures

Fig 4.1.2 : Designed Chamber

4.2 SYSTEM COMPONENTS

The system consists of the following major components:

Compressor: Responsible for compressing refrigerant and maintaining circulation

Evaporator: Absorbs heat from the storage chamber

Condenser: Rejects heat to the surroundings

Ultrasonic Humidifier: Generates fine mist for humidity control

Airflow System (Fan and Duct): Ensures uniform distribution of air

Sensors: Monitor temperature and humidity

Control Unit: Regulates system operation automatically.

4.3 METHODOLOGY

The methodology followed a structured engineering approach:

Phase 1: Design and Analysis

The methodology adopted in this study follows a systematic engineering approach, beginning with theoretical analysis and progressing towards practical implementation and performance evaluation. Initially, an extensive literature review was conducted to identify the optimal storage conditions for pineapple and to understand the limitations of existing refrigeration systems.

Based on the findings, key design parameters such as temperature range, relative humidity, and airflow rate were established. The system was then designed using standard thermodynamic principles, including cooling load calculations and component sizing. The vapour compression refrigeration cycle was selected due to its reliability and efficiency, and R600a refrigerant was chosen for its eco-friendly properties.

Phase 2: Fabrication

The fabrication phase involved constructing an insulated chamber using polyurethane foam to minimize heat gain. Essential components such as the compressor, condenser, evaporator, fan, humidifier, and sensors were installed and integrated into the system. A microcontroller-based control unit was programmed to monitor temperature and humidity in real time and to regulate system operation accordingly.

Phase 3: Testing and Optimization

Testing was carried out under controlled conditions by storing pineapples inside the chamber and monitoring parameters such as temperature stability, humidity levels, and energy consumption. Data collected during testing was analysed to evaluate system performance and identify areas for optimization.

5. WORKING PRINCIPLE

The system operates on the vapour compression refrigeration cycle. The refrigerant absorbs heat from the storage chamber in the evaporator, resulting in cooling. The compressor increases the pressure and temperature of the refrigerant, which then releases heat in the condenser.

Humidity is controlled using an ultrasonic atomizer that produces fine water droplets. These droplets are distributed evenly by the airflow system, ensuring uniform humidity throughout the chamber.

The control system continuously monitors temperature and humidity and adjusts the operation of the compressor, fan, and humidifier accordingly.

6. CALCULATIONS AND PERFORMANCE ANALYSIS

6.1 COMPRESSOR PERFORMANCE

The performance of the compressor was evaluated based on its cooling capacity, power input, and coefficient of performance. The compressor provides a cooling capacity of 150 W while consuming a power input of 90 W.

The efficiency of the refrigeration system is expressed using the Coefficient of Performance (COP):

$$\mathrm{COP} = \frac{QL}{W}$$

Using the given values:

Cooling Capacity (Q_L) = 150 W

Power Input (W) = 90 W

$$\mathrm{COP} = \frac{150}{90} = 1.67$$

This indicates that for every unit of electrical energy consumed, the system produces 1.67 units of cooling, demonstrating satisfactory performance for a small-scale refrigeration system.

6.2 AIRFLOW AND HEAT TRANSFER

Efficient airflow is essential for maintaining uniform temperature and humidity within the storage chamber. The system is designed with an airflow rate of 90 m^3/hr, which ensures proper circulation around the stored pineapples.

The corresponding mass flow rate of air is calculated as 0.03 kg/s, considering standard air density.

The heat removal capacity due to airflow is determined using:

$$Q = m * C_p * \Delta T$$

where:

m = Mass flow rate of air

C_p = Specific heat capacity of air

ΔT = Temperature difference

Based on the system conditions, the heat removal capacity is found to be 301 W, which supports effective cooling and uniform heat distribution inside the chamber.

6.3 POWER CONSUMPTION

The total power consumption of the system includes the compressor, fan, ultrasonic mist maker, and UV-C module.

Total system power consumption = 168 W

The daily energy consumption is calculated as:

Energy = Power × Time

Assuming 24-hour operation:

Energy = 168 × 24 = 4032 Wh = 4.03 kWh/day

However, considering compressor cycling and intermittent operation of auxiliary components, the actual measured energy consumption is reduced to 2.32 kWh/day, indicating efficient system operation.

6.4 SYSTEM EFFICIENCY

The overall system efficiency is evaluated by considering all additional loads, including humidification and UV sterilization, which contribute to the total power consumption but not directly to cooling.

The overall system COP is therefore calculated as:

$$\mathrm{COP_{overall}} = \frac{Cooling\ Effect}{Total\ power\ Input} = \frac{150}{168} = 0.89$$

This reduced COP compared to the compressor COP is expected due to auxiliary energy consumption. Despite this, the system maintains acceptable efficiency while providing enhanced preservation features such as controlled humidity and microbial reduction.

7. FABRICATION

The fabrication of the modified refrigeration system was carried out with careful consideration of structural strength, thermal insulation, and hygienic storage conditions required for pineapple preservation. The process involved the assembly of mechanical, electrical, and control components into a compact and functional unit.

The outer structure of the chamber was constructed using rigid materials such as mild steel sheets or high-strength plastic panels to ensure durability and mechanical stability. The inner surface was lined with food-grade, corrosion-resistant material to maintain hygiene and prevent contamination of the stored pineapples.

To minimize heat gain from the surroundings, the chamber walls were insulated using materials such as polyurethane foam (PUF) or thermocol. Proper insulation plays a vital role in maintaining the desired temperature range of 7°C to 12°C and improving overall energy efficiency.

The refrigeration unit, consisting of the compressor, condenser, expansion device (capillary tube), and evaporator coil, was installed within the system. The evaporator coil was positioned inside the chamber to ensure effective cooling, while the compressor and condenser were placed externally for better heat dissipation.

An air circulation system was fabricated using a low-power axial fan and properly designed ducts. This arrangement ensures uniform airflow across all storage trays, maintaining consistent temperature and humidity throughout the chamber. The airflow system was designed to achieve approximately 20 Air Changes per Hour (ACH).[1],[8]

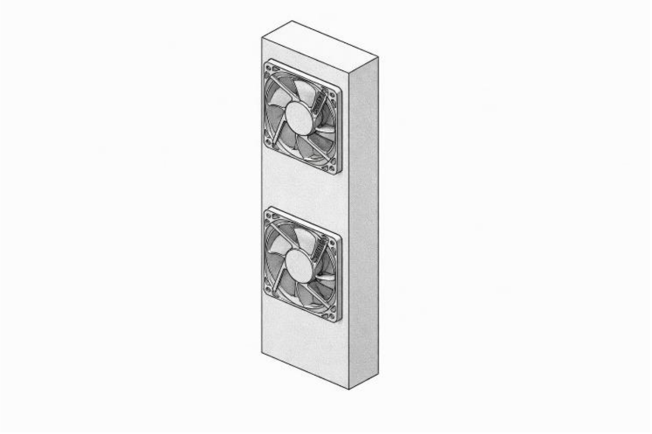


Fig 7.1 Isometric View of Duct

The humidity control system was integrated using an ultrasonic mist maker, which was installed inside the chamber to maintain relative humidity levels between 85% and 95%. Proper placement ensured uniform moisture distribution without direct water contact with the pineapples.

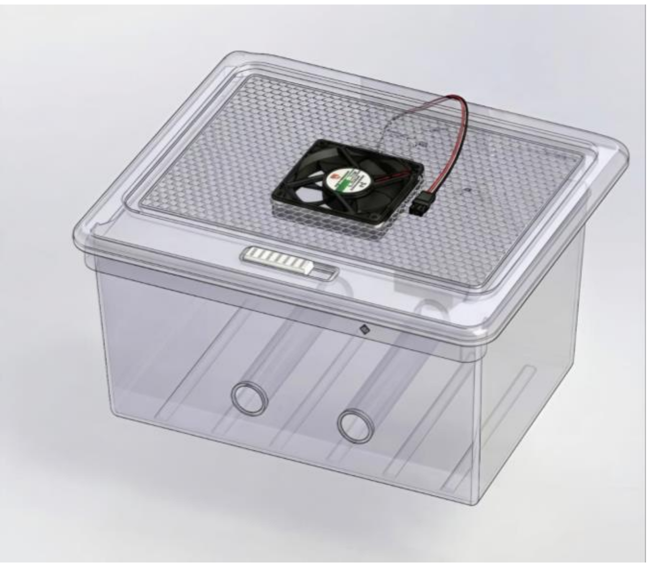


Fig 7.2 Humidifying Chamber

A UV-C light module was incorporated into the chamber for microbial control. The module was mounted in a position that allows effective air sterilization while avoiding direct and prolonged exposure to the fruit to prevent surface damage.[6],[7]

The tray system for holding pineapples was fabricated with adequate spacing to allow proper air circulation. The trays were designed using perforated or mesh-type materials to ensure uniform cooling and humidity distribution around each fruit.

Electrical connections, including wiring for the compressor, fan, humidifier, and UV module, were carefully assembled with proper insulation and safety measures. A control panel with switches and basic monitoring instruments was provided for easy operation.

Finally, the entire system was assembled, sealed, and tested for leakage, insulation effectiveness, and structural integrity. The fabricated unit was compact, efficient, and capable of maintaining the required environmental conditions for pineapple preservation.

Fig 7.3 Testing

Fig 7.4 Sample Testing

8. RESULTS AND DISCUSSION

The developed refrigeration system was tested under controlled environmental conditions to evaluate its effectiveness in preserving pineapples. The experimental results demonstrate that the system successfully maintained the required storage parameters and improved overall preservation performance.

During operation, a stable temperature range of 7°C to 12°C was consistently maintained within the chamber. This temperature range is ideal for slowing down the metabolic and microbial activity in pineapples, thereby extending their shelf life without causing chilling injury.

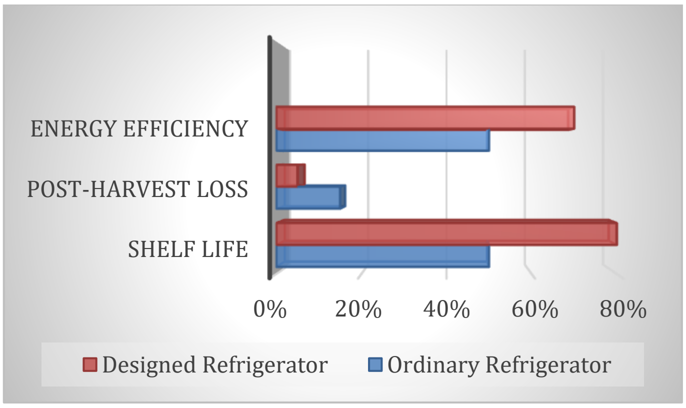
The system also maintained a relative humidity level between 85% and 90%, which is essential to minimize moisture loss from the fruit. This controlled humidity environment helped in preventing shrinkage, preserving weight, and maintaining the natural texture and appearance of the pineapples.

The airflow distribution within the chamber was found to be uniform, ensuring consistent temperature and humidity conditions across all storage trays. The designed airflow system (approximately 20 ACH) effectively eliminated localized variations, which are often responsible for uneven cooling and spoilage.

A noticeable reduction in weight loss and improvement in fruit freshness was observed during the storage period. The pineapples retained their firmness, colour, and overall quality for a longer duration compared to conventional storage methods.

In terms of energy performance, the system exhibited lower energy consumption due to optimized compressor operation, improved insulation, and efficient airflow management. The incorporation of controlled operation cycles further contributed to energy savings.

The integration of humidity control using an ultrasonic mist maker and optimized airflow design played a significant role in enhancing the storage environment. These features worked together to create a balanced condition that reduces dehydration and microbial growth.



Graph 8.1 Comparison of Ordinary and Designed Refrigerator

Overall, the results confirm that the developed system provides an effective solution for pineapple preservation by maintaining optimal storage conditions, improving product quality, and reducing post-harvest losses. The system demonstrates better performance compared to conventional refrigeration systems, particularly in terms of humidity control and energy efficiency.

9. CONCLUSION

The developed refrigeration system effectively meets the essential requirements for pineapple preservation by maintaining controlled temperature, humidity, and airflow conditions. The system consistently operated within the optimal temperature range of 7°C to 12°C and relative humidity range of 85% to 90%, ensuring an ideal environment for extending the shelf life of pineapples.

Experimental results confirm that the system provides improved preservation performance compared to conventional refrigeration methods. The integration of controlled humidity, uniform airflow distribution, and auxiliary features such as UV sterilization contributed to reduced weight loss, maintained freshness, and minimized microbial growth.

In addition, the system demonstrated energy-efficient operation with optimized power consumption, making it both economical and sustainable. Its simple design, cost-effectiveness, and ease of operation make it highly suitable for small-scale farmers, storage units, and agricultural applications, particularly in regions where post-harvest losses are significant.

Overall, the proposed system presents a practical and efficient solution for enhancing pineapple preservation and reducing wastage.

Future Scope :

Further improvements can be achieved by integrating control systems for real-time tracking of temperature, humidity, and system performance. Additionally, scaling up the design for large-scale storage applications and incorporating advanced control strategies can further enhance efficiency and usability.

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