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KUMASI, GHANA

COLLEGE OF ENGINEERING

FACULTY OF CHEMICAL AND MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

PROJECT REPORT

TOPIC: DESIGN, FABRICATION AND TESTING OF A MINI FREEZE DRYER

PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE AWARD OF

BSc. MECHANICAL ENGINEERING DEGREE

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ABSTRACT

This project focused on the design, fabrication and testing of a mini freeze dryer for small-scale food preservation.

Freeze drying, also known as lyophilization is a highly effective method of preservation whereby moisture is removed from food through sublimation. Existing freeze drying systems are often costly and not suitable for small-scale use prompting the need for a small and affordable alternative.

The mini freeze dryer was designed based on calculated heat and mass transfer requirements for sublimating 0.4 kg of water within 12-hour cycle. Key components, including an R600a based refrigeration system, oil-sealed vacuum pump, and aluminum drying chamber, were selected to achieve a target temperature of –30 °C under low pressure conditions. The system was fabricated using locally available materials. Testing was conducted using 0.4 kg of meat, with performance evaluated through amount of moisture loss and drying rate.

This work provides a cost-effective and compact solution for freeze drying, offering potential applications in household and small-scale commercial.

DECLARATION

The project report **DESIGN, FABRICATION AND TESTING OF A MINI FREEZE DRYER** is based on the work that was accomplished during our studies under the direction of **DR. P. O. TAWIAH**, we thereby sincerely swear.

The claims made and inferences made, according to us, are the results of our study. Also, we attest that the work in the report was completed by us and was original while working under the overall supervision of our supervisor. The work has not been submitted to any other institution for consideration of any other degree, diploma, or certificate at this university or any other in Ghana or outside of Ghana. Whenever we used data, theoretical analysis, or text from a different source, we properly credit that source in the report's text and provide their contact information in the references.

ACKNOWLEDGEMENTS

We want to first thank the Almighty God for His protection and wisdom throughout our entire period of research and investigations. We want to extend our gratitude to our coordinator, Dr. P. O. Tawiah, for his immense support and guidance throughout this entire period. We finally want to thank the department of mechanical engineering, KNUST who assisted us in many ways to see to the organization and finalize the report.

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1.0 CHAPTER ONE- INTRODUCTION

This chapter contains the background research, problem statement, title of the project, aim and objectives, justification, and the structure of the report.

1.1 BACKGROUND RESEARCH ON THE FREEZE DRYER

Background and Motivation

Lyophilization, or freeze drying, is a preservation method that is extensively employed in the pharmaceutical, biotechnology, and food industries (Wikipedia, 2025; Ruiton, 2021). It involves removing moisture from a product by sublimation under low pressure and temperature conditions, thereby maintaining its structure, nutritional value, and shelf stability. This project focuses on the development of a compact freeze dryer, approximately the size of a microwave, designed to efficiently process food products, for extended storage while maintaining quality. (Barnalab, 2023).

Historical Development of Freeze Drying

While determining which civilization first invented freeze-drying remains a challenge for researchers, we know that ancient societies, such as the Peruvian Incas, practiced an early form of freeze-drying by exposing food to freezing temperatures and removing water before storage. The Aymara people of the Andes, for example, developed a method to preserve potatoes known as "chuno," utilizing high-altitude freezing and sun exposure to remove moisture and extend shelf life. By 1890, German scientist Albert Altmann successfully freeze-dried organ tissue using sublimation. The modern lyophilizer was invented in 1905 when Benedict and Manning developed a machine, initially referred to as a chemical pump, to dry and preserve blood tissues. In 1906, French scientist Jacques-Arsène d'Arsonval refined the freeze-drying process by removing water at low temperatures, leading some to credit him as the inventor of modern freeze-drying (ShepherdFoods, 2023). Further advancements came in 1910 when L. F. Shackell introduced an electric pump to enhance the process. The first U.S. patent for a modern freeze dryer was issued in 1934 to Elser, whose design incorporated a cold trap and dry ice (FamilyCanning, n.d.; FreezeDriedExpert, 2024).

Evolution and Technological Advancements

Throughout the 1930s and World War II, freeze-drying became a vital technology for preserving biological materials and plasma, ensuring life-saving medical treatments remained viable in the field. This innovation played a crucial role in military medicine by allowing blood donations to be stored without refrigeration. Following the war, freeze-drying found widespread application in the food industry(NewLifeScientific, 2023; FamilyCanning, n.d.. Nestlé pioneered the development of freeze-dried instant coffee in response to Brazil's coffee surplus, creating a product with an extended shelf life. The space race of the 1960s further propelled freeze-drying technology, with NASA utilizing the method to produce lightweight, nutritious, and long-lasting food for astronauts. Freeze-dried meals became commercially popular, and even freeze-dried ice cream emerged as a novelty item in museums and space centers. (FreezeDriedExpert, 2024; ChinaFreezedried, 2024).

Modern Trends in Freeze-Drying

Today, freeze drying is an essential process across multiple industries, including pharmaceuticals, biotechnology, and specialty food production. Advancements in material science, vacuum systems, and refrigeration have led to the development of smaller, more efficient freeze dryers. Manufacturers continue to seek cost-effective solutions by incorporating pre-treatments such as infrared heating, osmotic dehydration, and ultrasound to reduce energy consumption. Some designs have introduced spray nozzles or microwaves in the drying chamber to enhance efficiency. This project will contribute to this ongoing evolution by designing a compact, user-friendly freeze dryer. By integrating modern refrigeration and vacuum systems into a small-scale unit, this project aims to create an efficient and affordable solution for individuals and small businesses looking to preserve high-quality food products, particularly meat, for long-term storage. Through these developments, freeze-drying technology will continue to expand, providing innovative solutions for food preservation and extending its benefits to a broader range of users. (Barnalab, 2023; FreezeDriedExpert, 2024

1.2 PROBLEM STATEMENT

Food spoilage is a major challenge, leading to waste, financial loss, and food insecurity. Numerous preservation techniques, like dehydration and refrigeration, have drawbacks, such as limited shelf lives, nutritional deterioration, and a need for a constant power source. One of the best preservation methods is freeze drying, which eliminates moisture without sacrificing the nutritional content, flavor, or structure of food. However, the cost, size, and industrial design of the current freeze dryers prevent households, small enterprises, and local food producers from using them. The lack of an affordable, compact, and energy-efficient freeze dryer for food preservation creates a gap in the market, limiting options for long-term food storage. Individuals and small-scale food processors might increase the shelf life of perishable commodities like meat and apples, decrease spoilage, and guarantee food availability without depending on refrigeration with an affordable and easy-to-use freeze dryer.

By providing a more approachable, effective, and economical design, this project seeks to create a workable freeze-drying solution that gets beyond the drawbacks of current systems. The project will help a larger spectrum of consumers by addressing this demand and promoting sustainable food preservation, waste reduction, and food security.

1.3 AIM OF THE PROJECT

This project aims to design, fabricate and test a mini freeze dryer.

1.4 SPECIFIC OBJECTIVES OF THE PROJECT

- **Conduct a Literature Review on Freeze Dryers and the Freeze-Drying Process**

  This objective involves researching existing freeze-drying technologies, their working principles, and the science behind the process. It includes studying different types of freeze dryers, their components (such as vacuum pumps, refrigeration systems, and heat exchangers), and their applications. The literature review will help identify best practices, common challenges, and cost-effective solutions for building a freeze dryer.

- **Develop and Evaluate Design Concepts**

  Based on insights from the literature review, various design concepts will be proposed for the freeze dryer. These designs will be evaluated based on features such as efficiency, cost, ease of construction, and performance in achieving low temperatures and deep vacuum levels. The most suitable design will be selected for implementation.

- **Construct the Freeze Dryer**

  This phase involves assembling the freeze dryer according to the selected design. Key tasks include selecting and integrating components such as the vacuum pump, refrigeration system, insulation, heat exchangers, and control systems. The construction process will also involve fabricating the chamber and ensuring all parts function cohesively.

- **Testing of the Freeze Dryer**

  Once constructed, the freeze dryer will undergo testing to ensure it meets the required performance criteria. Testing will include evaluating vacuum levels, cooling efficiency, drying effectiveness, and overall reliability. The final goal is to achieve a fully functional and efficient freeze-drying system.

1.5 SUMMARY OF METHODOLOGY

The methodology for the development of the compact freeze dryer centers on a systematic approach encompassing system design, component selection, and assembly to achieve optimal freeze-drying results, particularly focused on preserving food quality.

1. System Design: The initial phase involves creating a detailed design blueprint for the freeze dryer. This design will incorporate a chamber capable of reaching sub-zero

temperatures, specifically targeting a minimum temperature of -40°C to ensure effective sublimation. The design will prioritize a space-efficient structure, ideally around the size of a microwave, to meet the project's aim of compactness for easy usability in domestic and small-scale commercial settings.

2. Component Selection: Careful selection of materials and components is critical to the success of the freeze dryer. All materials will be chosen based on their ability to withstand extreme temperatures and vacuum conditions. Components such as heating elements, vacuum pumps, and insulation materials will be specified to ensure optimal performance while minimizing power consumption. The vacuum system will be designed to maintain an optimal level of less than 100 mTorr, enabling efficient moisture removal.

3. Assembly: The construction phase will involve the meticulous assembly of all selected components according to the developed design. This will include the integration of insulation to minimize heat loss, installation of the vacuum system, and setting up the control systems to monitor and maintain desired temperature and pressure levels. Safety features will also be incorporated to ensure user protection during operation.

4. Testing and Validation: Post-assembly, the prototype will undergo a series of tests to validate its performance against the project's objectives. This will include tests for moisture reduction efficiency, temperature stability, vacuum integrity, and overall product quality. Specific characteristics of the freeze-dried products, such as strength,

color uniformity, dryness, porosity, and the absence of particulates, will be assessed to ensure the prototype meets established standards.

5. Iterative Improvement: Based on the results of the initial testing, iterative improvements will be implemented. This stage may involve refinements in the design and functionality to further enhance the operational efficiency and user-friendliness of the freeze dryer.

Through this comprehensive methodology, the project aims to accomplish the development of an affordable, compact, and energy-efficient freeze dryer, providing a practical solution for long term food preservation while fostering sustainability and reducing food waste.

1.6 ORGANIZATION OF THE REPORT

This report is divided into five chapters, each addressing key aspects of the Freeze Dryer project:

- Chapter 1: Introduction – It provides introduction on freeze-drying, the problem statement, objectives, significance and scope. The introduction gives a clear picture of the origin and purpose of the project. The problem statement clearly defines the problem this project aims to address. It also includes the aims, which provides a clear picture of where we are headed and the objectives discuss the several activities, we will be doing to accomplish our goal.

- Chapter 2: Literature Review – The literature review talks about how freeze-drying works and where it's used. It also explains why a well-designed, efficient freeze dryer is important. The principle to which a freeze dryer works with is also discussed. We explore the freeze-drying process, the different types of freeze dryers, and why they matter in preserving food, medicine, and other materials

- Chapter 3: Conceptual Designs – It covers system design and specifications, functional requirements, component selection, evaluation criteria table and assembly of the freeze dryer.

- Chapter 4: Conclusion and Recommendations – This chapter summarizes findings, discusses challenges, and suggests improvements.

- Chapter 5: Outstanding Work – This chapter talks about future work to be done.

2.0 CHAPTER TWO-LITERATURE REVIEW

This chapter presents a review of research findings related to freeze-drying technology, including recent mechanical advancements proposed by engineers and researchers to improve the efficiency and affordability of small-scale freeze dryers. A discussion of previous studies on freeze-drying principles, system components, and innovations is also provided.

This research focuses on the need for an accessible and energy-efficient freeze dryer for small-scale applications, specifically for preserving apples. The demand for food preservation methods has increased due to concerns over food waste, seasonal availability, and the desire to maintain nutritional value over long storage periods. Freeze-drying is one of the most effective preservation techniques, as it retains food quality better than traditional drying methods. However, commercial freeze dryers are often expensive and energy-intensive, making them impractical for household or small-scale use.

The rising interest in small-scale food preservation has led to advancements in freeze-drying technology, including improved vacuum pumps, energy-efficient refrigeration systems, and automated drying control mechanisms. Additionally, researchers have explored optimization techniques to reduce drying time and minimize energy consumption while maintaining product integrity. This study seeks to build upon these advancements by designing a compact, cost-effective freeze dryer specifically for drying apples, ensuring efficient moisture removal while preserving texture, flavor, and nutritional content.

2.1 HISTORICAL PERSPECTIVE

Drying from the frozen state is not uncommon in nature. In the winter, snow vanishes along the roads in dry cold air without melting. In Central Siberia, scientists have found the large bodies of mammoths that have been progressively freeze-dried during the past 15,000 years. In the Peruvian high plateau, the Incas reportedly stored, in their tambos, meat that had been dried in the sun at the reduced pressure of the Andes.

Scientific interest in freeze-drying began at the turn of the twentieth century with a publication by Bordas and d'Arsonval at the French Academy of Sciences. Following that publication, Altman and later Gersh used this technique to prepare undistorted dry samples for microscopy. Ronald Greaves, in Cambridge, UK, began his work along those lines in the 1930s by preparing dry suspensions of living bacteria. However, this technique still was only familiar to a handful of scientists in isolated laboratories. Then came World War II. With tens of thousands of casualties on the battlefields, human plasma was in great need, and freeze-drying again entered the limelight. Thanks to Greaves in England, François Henaff in France, and Earl Flosdorf in the United States, thousands of liters of blood were processed to isolate plasma, which was then preserved by freezing and drying. As the use of lyophilization expanded, the process began to be industrialized. Loire, Stokes, Edwards, and others designed and built the first equipment for the purpose. Called "lyophilization" by Flosdorf, the process faced its first major challenge under Sir Ernst Boris Chain, who used the technique to preserve antibiotics. Given Chain's results turned to lyophilization to prepare vaccines and, later on, to refine blood fractions. By the mid-1950s, many industries were already using freeze drying to preserve pharmaceutical and biological products, as were the physicians and surgeons who developed tissue-banking for plastic and reconstructive surgery. Drs. Hyatt, Bassett, and Meryman of the United States Navy were among the early pioneers in the field.

2.2 ADVANTAGES

- Stored in a dry state, so stability problems are few.
- Product is dried without elevated temp.
- Constituents of dried material remain homogenously dispersed.
- Rapid reconstitution time.
- Freeze-drying can preserve food and make it very lightweight. (Barnalab, 2023; FamilyCanning, n.d.)
- In some specialized laboratories, scientists are developing more sophisticated processes that combine freeze-drying technology with electron microscopy, biochemistry, and refined surgery. (Barnalab, 2023; FamilyCanning, n.d.)

- At the same time, the cosmetics industry is increasing its use of lyophilization to help prepare beauty masks, hair dyes, and sophisticated support for face creams. (Barnalab, 2023; FamilyCanning, n.d.)
- Chemical industries also are beginning to use freeze-drying to prepare refined chemicals, catalysts, and selective filters. (Wikipedia, 2025; FamilyCanning, n.d.)
- If a freeze-dried substance is sealed to prevent the reabsorption of moisture, the substance may be stored at room temperature without refrigeration and be protected against spoilage for many years. (EREA, 2024; Wikipedia, 2025).
- Preservation is possible because the greatly reduced water content inhibits the action of microorganisms and enzymes that would normally spoil or degrade the substance. (Barnalab, 2023; FamilyCanning, n.d.)
- Freeze-drying also causes less damage to the substance than other dehydration methods using higher temperatures. (Barnalab, 2023; FamilyCanning, n.d.)
- Freeze-drying does not usually cause shrinkage or toughening of the material being dried. (Barnalab, 2023; FamilyCanning, n.d.)
- Flavors and smells generally remain unchanged, making the process popular for preserving food. (EREA, 2024; FamilyCanning, n.d).

2.3 DISADVANTAGES

- Large objects take a long time to freeze-dry. (Wikipedia, 2025; Reddit, 2020).
- If too much heat is added, the material's structure could be altered. (Wikipedia, 2025; Reddit, 2020).

- Freezing damage can occur with labile products such as fruits (e.g. Berries, bananas), vegetables (e.g. Mushrooms, spinach), certain proteins and peptides, antibiotics and vaccines (FamilyCanning, n.d.; Reddit users on HarvestRight, 2023)
- Expensive unit operation because pumps are more expensive. (Wikipedia, 2025; Barnalab, 2023)
- Extremely low water content in the final product can result in destabilization. (Wikipedia, 2025; Barnalab, 2023)
- Freeze-dried materials easily absorb moisture from the air, requiring proper packaging and storage to prevent spoilage. (FamilyCanning, n.d.; Reddit users on HarvestRight, 2023)

2.4 CHARACTERISTICS OF FREEZE-DRIED PRODUCTS

- **Weight Reduction:** One of the most noticeable characteristics of freeze-dried food is its significantly reduced weight. Water constitutes a substantial proportion of most foods, and when it is removed during the freeze-drying process, typically leaving only about 1% moisture—the resulting product becomes extremely lightweight. This weight reduction makes freeze-dried foods particularly beneficial for applications where minimizing load is crucial, such as space travel, mountaineering, and military rations. For instance, astronauts on long missions require nutrient-dense foods that are lightweight, compact, and easy to rehydrate. (Wikipedia, 2025; EREA, 2024)

- **Extended Shelf Life:** Freeze-dried foods can last for an exceptionally long time when stored properly. The absence of water, combined with airtight, vacuum-sealed packaging, significantly slows down microbial growth and oxidative reactions that lead to food spoilage. Depending on the quality of the freeze-drying process and storage conditions, freeze-dried foods can have a shelf life of up to 20–25 years. However, commercial mass-produced freeze-dried foods often have shorter shelf lives, sometimes as short as six months to a year. This is typically due to quicker, less thorough drying processes or the lack of vacuum-sealed packaging. In contrast, properly freeze-dried and stored food maintains its quality for decades, making it ideal for emergency preparedness and long-term storage. (FamilyCanning, n.d.; Barnalab, 2023)

- **Preservation of Nutrients and Vitamins:** A key advantage of freeze-drying is that it preserves almost all the nutrients, vitamins, and minerals present in the original food. Unlike other drying methods that expose food to high temperatures—potentially destroying heat sensitive nutrients—freeze-drying occurs at sub-zero temperatures, ensuring that essential vitamins and minerals remain intact. This makes freeze-dried food an excellent choice for individuals who prioritize nutrition, including outdoor enthusiasts, health-conscious consumers, and survivalists. (FamilyCanning, n.d.; Barnalab, 2023)

- **Rehydration Capability:** Another unique feature of freeze-dried food is its ability to rehydrate quickly and efficiently. When exposed to water, freeze-dried foods absorb moisture and return to a state similar to their fresh form. This rehydration ability is particularly beneficial for fruits, vegetables, meats, and complete meals. Some foods, such as meats, naturally absorb only the required amount of water, ensuring they regain their original texture and consistency. Others, such as bananas or other soft fruits, need careful rehydration to prevent them from becoming overly soggy. Additionally, freeze-dried meals do not need to be consumed dry; they can be gently rehydrated using a steam cooker or microwave. (Wikipedia, 2025; EREA, 2024)

- **Minimal Transfer of Smells and Tastes:** Unlike other preservation methods, freeze-drying ensures that different foods processed together do not transfer their flavors or odors to each other. This means that a batch containing a mix of meats, vegetables, and fruits will not result in unintended flavored combinations. This unique property is particularly useful when freeze drying diverse food items in a single cycle. (FamilyCanning, n.d.; Barnalab, 2023)

- **Ease of Grinding and Powdering:** Since freeze-dried food contains virtually no water, it becomes extremely brittle and easy to grind. Freeze-dried ingredients can be effortlessly crushed into fine powders using a basic kitchen blender. This property is useful in culinary applications where powdered ingredients are needed, such as fruit powders for smoothies, vegetable powders for soups, or meat powders for seasoning. The resulting powders are highly concentrated in flavor and nutrients, making them versatile for various food preparations. (FamilyCanning, n.d.; Barnalab, 2023)

2.5 PRINCIPLES OF FREEZE DRYING

Freeze drying is a process that relies on the principle of sublimation, where ice transitions directly into vapor without passing through the liquid phase. This process is only possible under specific temperature and pressure conditions, typically below the triple point of water, which occurs at 0.01°C and 611.73 Pa. By maintaining a low-pressure environment, freeze drying effectively removes moisture while preserving the integrity and structure of the material. (Wikipedia, 2025; Ruiton, 2021).

The triple point of water is a crucial concept in freeze drying. It represents the unique temperature and pressure combination where solid, liquid, and gas phases can coexist. Operating below this point ensures that ice transitions directly to vapor, preventing the formation of liquid water. The presence of liquid can degrade or structurally damage the material, making precise temperature and pressure control essential to the efficiency of the freeze-drying process. (Wikipedia, 2025; Ruiton, 2021).

A vacuum system plays a fundamental role in the process by reducing atmospheric pressure inside the freeze dryer. Lowering the pressure decreases the boiling point of water, enabling ice to sublimate at lower temperatures. This is particularly beneficial for heat-sensitive materials, such as biological samples or food products, as it prevents thermal degradation. The vacuum pump continuously removes water vapor, ensuring that the low-pressure environment is maintained for efficient sublimation. However, pressure control must be carefully balanced. If the pressure is too high, sublimation slows down, leaving residual moisture in the material. Conversely, if the pressure is too low, the rate of heat transfer decreases, prolonging the drying process. Therefore, striking the right balance between pressure and temperature is critical to achieving efficient moisture removal and preserving product quality. (Wikipedia, 2025; Ruiton, 2021).

The freeze-drying process occurs in three main phases. First, the material is frozen to solidify its water content. Slow freezing results in larger ice crystals that facilitate sublimation, whereas rapid freezing creates smaller ice crystals that may slow the drying process. In the second phase, known as primary drying, heat is applied under reduced pressure to drive sublimation. Most of the moisture is removed during this stage, leaving behind a structurally intact but porous material. The final phase, secondary drying, involves slightly increasing the temperature to remove any residual moisture bound to the material. This ensures long-term stability by preventing microbial growth and oxidation. (Wikipedia, 2025; Ruiton, 2021).

A phase diagram of water provides valuable insight into how different temperature and pressure conditions affect its state. In freeze drying, staying below the triple point guarantees that ice transitions directly to vapor, bypassing the liquid phase. This prevents structural collapse and helps retain the material's original shape and properties. (Wikipedia, 2025; Ruiton, 2021).

Freeze drying is an advanced preservation technique that leverages sublimation, vacuum pressure control, and the triple point of water to achieve moisture removal while maintaining the quality of the material. By carefully regulating pressure and temperature, the process preserves nutrients and structural integrity, making it a crucial technique in food preservation, pharmaceuticals, and scientific research. (Wikipedia, 2025; Ruiton, 2021).

The phase diagram of water, shown in Figure below, illustrates the relationship between temperature and pressure, highlighting the triple point and sublimation region, which are critical in freeze drying.

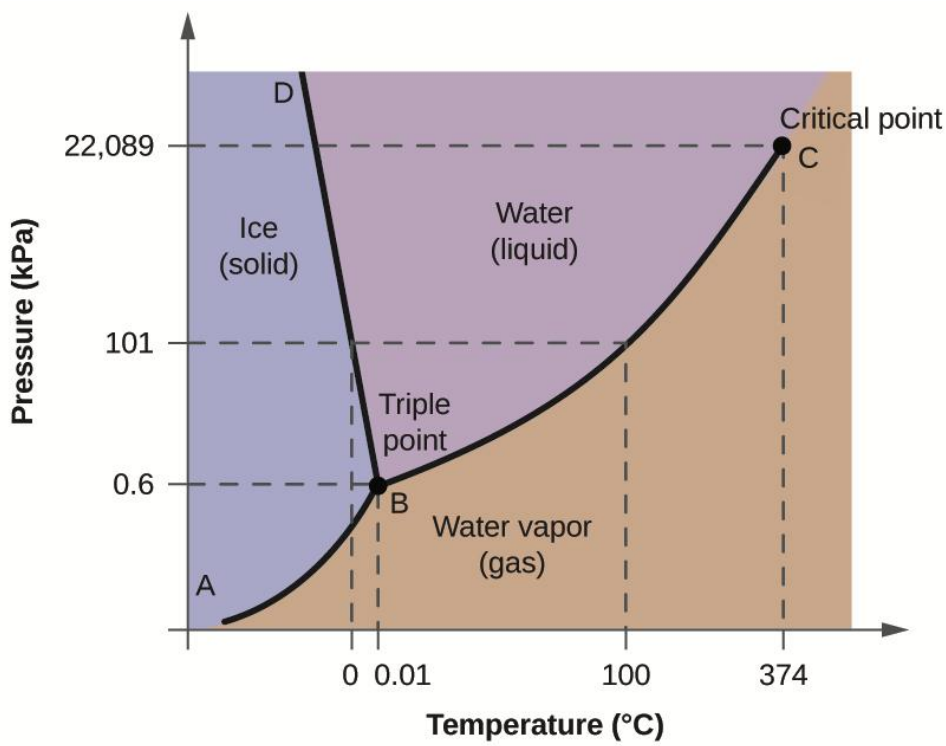


Figure 1 Phase Diagram of Water

Source: https://courses.lumenlearning.com/suny-chem-atoms-first/chapter/phase-diagrams-2/

2.6 FREEZE DRYING PROCESS

Freeze drying happens in three main stages:

1. Freezing

2. Primary Drying (Sublimation)

3. Secondary Drying (Desorption)

1. Freezing Phase

Freezing is the most crucial step in freeze drying, and there are several ways to do it. Materials can be frozen using a standard freezer, a chilled liquid bath (shell freezer), or directly on temperature-controlled shelves in a freeze dryer. The key is to cool the material below its triple point, ensuring that water transitions directly from ice to vapour instead of melting into a liquid. This helps preserve the material's physical structure.

For effective freeze drying, larger ice crystals are preferred because they make sublimation easier. These can be formed by slow freezing or a technique called annealing, where the product is first frozen quickly and then briefly warmed to encourage crystal growth. However, when working with biological materials, large ice crystals can rupture cell walls, leading to poor drying results. To avoid this, freezing must be done rapidly. Annealing is also useful for materials that tend to precipitate, as it helps form a more stable ice structure. (Wikipedia, 2025; Ruiton, 2021).

2. Primary Drying Phase (Sublimation)

The second phase, primary drying, involves lowering the pressure and adding heat to promote sublimation—the direct conversion of ice into vapor.

A vacuum pump speeds up this process, while a cold condenser acts as a trap, capturing the water vapor and turning it back into ice. This prevents moisture from reaching the vacuum pump and damaging it.

During this stage, about 95% of the water content is removed. However, primary drying must be carefully controlled—if too much heat is applied, it can damage the material or change its structure. This phase is typically the longest part of the freeze-drying process. (Wikipedia, 2025; Ruiton, 2021).

3. Secondary Drying Phase (Desorption)

The final step, secondary drying, removes water molecules that are still loosely bound to the material. By increasing the temperature slightly higher than in the primary drying phase, these remaining water molecules break free and evaporate.

After freeze drying, the material retains a porous structure, which makes it easier to rehydrate later. Before sealing, the vacuum is often replaced with an inert gas to protect the product. Most materials can be dried to 1-5% residual moisture. (Wikipedia, 2025; Ruiton, 2021).

2.7 BASIC COMPONENTS OF FREEZE DRYERS

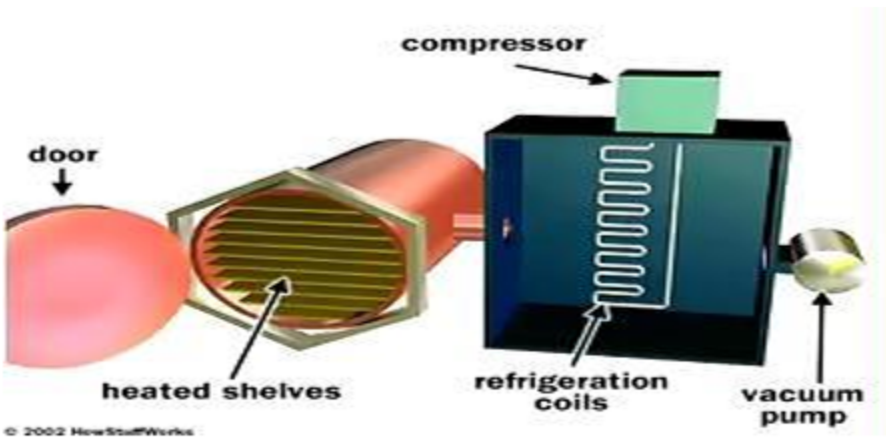


Figure 2 Components of Freeze Dryer

Source: https://m.indiamart.com/proddetail/freeze-drying-16064152573.html

A freeze dryer is made up of several key parts, all working together to remove moisture while keeping the material's structure intact. Here's a breakdown of the basic components and what they do:

1. **Refrigeration System:** This is the core of the freeze dryer, responsible for cooling and freezing. It includes components such as compressors, condensers, evaporators, and

expansion valves. These elements operate in a cycle to produce low-temperature refrigeration effects. (UKessays, 2023)

- **Compressor:** An essential part of the refrigeration system, the compressor circulates refrigerant to keep the vacuum chamber at freezing temperatures. Prior to being sent through the system, it compresses the refrigerant, raising its temperature and pressure. This allows the material inside the chamber to freeze quickly, maintaining its quality and structure. (UKessays, 2023)

Figure 3 Compressor

Source: https://carlisaenterprises.com/products/fridge-compressor-1-6hp

- **Evaporator:** One essential part of a freeze dryer's refrigeration system is the evaporator. By permitting low-pressure refrigerant to evaporate, it absorbs heat from the drying chamber or condenser and cools the system to the necessary low temperatures. (UKessays, 2023)

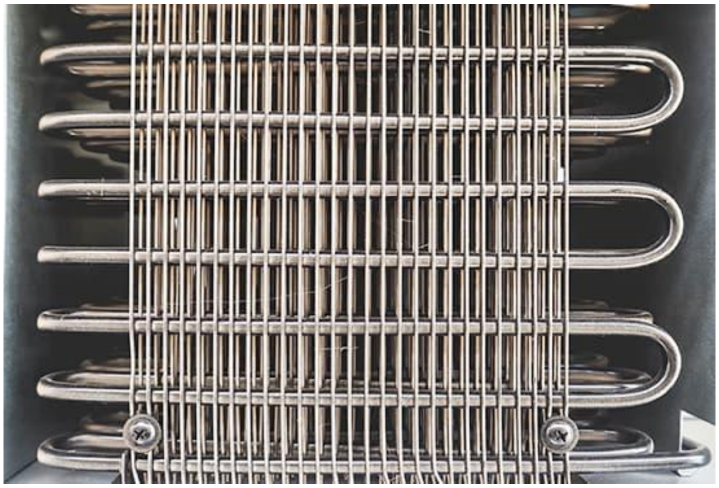


Figure 4 Evaporator

Source: https://intersam.es/en/what-is-a-thermostatic-expansion-valve-tev-and-what-are-its-functions/

- **Expansion Valve:** The expansion valve controls the flow of refrigerant into the evaporator. In order to ensure that the refrigerant can absorb heat effectively, it lowers its pressure before it enters the evaporator. In order to maintain steady cooling conditions, the expansion valve automatically modifies the refrigerant flow in response to temperature variations. (UKessays, 2023)

Figure 5 Expansion Valve

Source: https://intersam.es/en/what-is-a-thermostatic-expansion-valve-tev-and-what-are-its-functions/

- **Condenser:** By turning water vapor into solid ice, the condenser of a freeze dryer extracts it from the drying chamber. To preserve a vacuum, expedite drying, and shield the vacuum pump from moisture damage, it runs at extremely low temperatures.

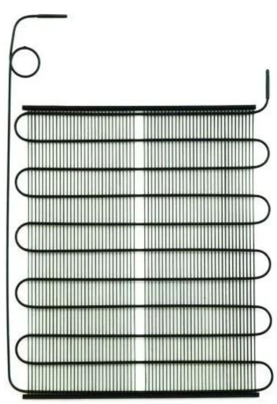


Figure 6 Condenser

Source: https://m.indiamart.com/proddetail/refrigeration-condenser-11903350755.html

Vacuum System: This system maintains a low-pressure environment inside the drying chamber to facilitate the sublimation of water at low temperatures. It consists of a vacuum pump, vacuum gauge, pipelines, and valves, ensuring the required vacuum level is achieved. (Barnalab, 2023; Reddit engineers, 2023).

- . **Vacuum Pump:** The vacuum pump is responsible for removing air from the vacuum chamber to create low-pressure conditions essential for sublimation. Air molecules are continuously drawn out and released via an exhaust system. The vacuum pump's lubricating system and filters provide effective operation

Figure 7 Vacuum Pump

Source: https://www.vikaspumps.com/ghana/vacuum-pump.html

2. **Drying Chamber:** This is the enclosed space where the materials to be dried are placed. It is designed to be well-sealed and insulated. During the drying process, the chamber maintains low temperatures and vacuum conditions to enable moisture sublimation and removal. In the drying chamber is the tray or shelves The material is placed on trays or shelves inside the chamber to help spread out the product evenly, ensuring it dries consistently. (UKessays, 2023)

3. **Heating System:** This system provides the necessary heat to promote the sublimation of moisture from the material. It typically includes heaters, temperature sensors, and control units, allowing precise temperature regulation within the chamber.

- **Heating Trays / Shelves:** The tray itself in a freeze dryer serves as the platform where the material to be freeze-dried is placed. It is typically made of stainless steel or aluminum to ensure efficient heat transfer. The tray is designed to hold the material in a uniform layer, allowing for even freezing and sublimation. It also helps in organizing the products inside the vacuum chamber, maximizing space utilization. The sublimation process is accelerated without melting by applying controlled heat to the frozen material using heating trays or shelves. For effective heat conduction, these trays are usually composed of stainless steel or aluminum. Low-level heat is produced by heating elements built into the trays.

Figure 8 Heating shelves

Source: https://heatertray.com.au/product/heater-tray/

4. **Electrical Components:** All the freeze dryer's mechanical and refrigeration systems are powered and managed by the electrical components. These include relays, circuit breakers, power supply units, and sensors that keep an eye on pressure and temperature. These parts shield the freeze dryer from power fluctuations and possible malfunctions. (UKessays, 2023)

5. **Frame**: The machine's body houses all its internal parts and offers structural support. It shields the machine from outside damage since it is made of sturdy materials like metal or high-strength plastic. In order to prevent overheating, particularly for the compressor and electrical components, ventilation systems and cooling fans are built into the body. The body's insulated construction aids in preserving the low temperatures needed for freeze-drying.

2.8 KEY FACTORS THAT AFFECT THE FREEZE DRYING PROCEES

The effectiveness and success of the freeze-drying process are influenced by a number of factors.

The sublimation rate is significantly influenced by the product's temperature. Although sublimation is slowed considerably at lower temperatures, the product's quality is maintained. Maintaining the right temperature balance is key to achieving effective drying while keeping the product intact.

Drying speed is also influenced by the product's surface area. Due to increased exposure, smaller, thinner things dry more quickly than larger, thicker ones.

Another important factor that affects sublimation is the level of vacuum inside the chamber. Water's boiling point is lowered by a stronger vacuum, which allows the evaporation of moisture happen quickly. (Barnalab, 2023; UKessays, 2023).

2.9 TYPES OF FREEZE DRYERS

Freeze drying is a widely used preservation technique, playing a vital role in industries such as food processing and pharmaceuticals. As the demand for long term storage solutions grows, different types of freeze dryers have been designed to meet specific needs. Here's a breakdown along with representative images for each:

1. **Laboratory (Batch) Freeze Dryers**

   Compact, benchtop devices called laboratory freeze dryers are made for small-scale testing and research. They assist scientists to preserve biological samples, medications, and food ingredients by eliminating moisture while keeping structural integrity. These freeze dryers are perfect for quality control and experimental work because they offer exact temperature and pressure control. Researchers can keep an eye on the procedure in real time thanks to its transparent chambers and digital control panels. (UKessays, 2023)

Figure 9 Batch Freeze Dryer

Source: https://vikumer.com/lgj-20-laboratory-basic-research-freeze-dryer/

2. **Pilot Freeze Dryer**

Pilot freeze dryers bridge the gap between laboratory research and full-scale industrial production. These medium-sized facilities are intended for process development, clinical trials, and small-scale production. Before committing to large-scale operations, businesses can hone their freeze-drying methods thanks to their increased capacity and automated features. Industries that need high-quality, consistent results without the cost of whole industrial equipment depend on pilot freeze dryers. (UKessays, 2023)

Figure 10 Pilot Freeze Dryer

Source: https://www.freezedrymachine.com/product/fd-50f-series-automatic-pilot-freeze-dryer-4kg-batch-8kg-24-hours/

3. **Industrial Freeze Dryer**

Industrial freeze dryers are large-scale systems employed in the biotech, pharmaceutical, and food sectors for mass production. With several drying racks and automatic controls to guarantee effectiveness and consistency, these machines manage large volumes. Commercial-scale preservation of perishable items depends on industrial freeze dryers, which allow food and medication to be transported and stored for extended periods of time without losing their vital qualities. (UKessays, 2023)

Figure 11 Industrial Freeze Dryer

Source: https://vikumer.com/commercial-food-freeze-dryers/fd-5rs-freeze-dryer/

2.10 APPLICATIONS OF FREEZE-DRYING TECHNOLOGY

- **Pharmaceutical Preservation**

  Freeze drying, commonly known as lyophilization, is a key method for stabilizing vaccines, biologics, and moisture-sensitive pharmaceuticals. This process ensures that injectable drugs and biotechnology-based treatments retain their potency, extending their shelf life and making them easier to transport and store without degradation. (Barnalab, 2023; FamilyCanning, n.d.)

- **Food Processing and Storage**

The food industry relies on freeze drying to preserve various products, including instant meals, dried fruits, and vegetables. By removing moisture while maintaining taste, texture, and nutritional value, this method extends shelf life and enhances product quality. It is particularly popular for premium brands, as well as coffee, herbs, and spices, where maintaining aroma and flavour is essential. (Barnalab, 2023; FamilyCanning, n.d.)

- **Space Missions and Astronaut Nutrition**

  Freeze drying plays a crucial role in space travel by providing lightweight, nutrient-dense meals for astronauts. Since removing moisture significantly reduces weight while keeping essential nutrients intact, this method ensures that space crews have access to safe, long-lasting food during extended missions. (Barnalab, 2023; FamilyCanning, n.d.)

- **Biotech and Scientific Research**

  In research labs and biotechnology fields, freeze drying is a reliable technique for preserving enzymes, proteins, cell cultures, and other biological materials. By eliminating moisture, these substances can be stored for extended periods without compromising their integrity, which is vital for repeatable experiments and scientific studies. (Barnalab, 2023; FamilyCanning, n.d.)

- **Nutritional Supplements and Wellness Products**

  The nutraceutical industry benefits greatly from freeze drying, as it helps maintain the potency of probiotics, vitamins, herbal extracts, and other health-focused products. This method ensures that essential nutrients remain intact, allowing supplements to retain their effectiveness over time. (Barnalab, 2023; FamilyCanning, n.d.)

- **Beauty and Skincare Applications**

  In the cosmetic industry, freeze drying is used to preserve active ingredients like collagen, peptides, and botanical extracts. This method ensures that these compounds remain pure and effective until they are rehydrated for use in skincare and beauty formulations, enhancing product quality and performance. (Barnalab, 2023; FamilyCanning, n.d.)

3.0 CHAPTER THREE-CONCEPTUAL DESIGN

The approach involves functional and design requirements, conceptualization, evaluation criteria table, component selection and assembly of the freeze dryer.

3.1 FUNCTIONAL REQUIREMENTS

- **Drying capacity:** The system must be able to freeze dry the product in a single cycle.

- **Vacuum System:** The vacuum pump must be able to reduce chamber pressure between 0.01 to 1mbar.
- **Refrigeration system:** The freezer must cool the chamber to -40°C or lower to freeze the food before drying.
- **Heating System:** The system must provide controlled and evenly distributed heating up to 60°C to facilitate sublimation without cooking the food.
- **Chamber Design:** The Vacuum chamber must be airtight, thermally insulated and withstand vacuum pressure without deformation.
- **Material Compatibility:** Components in contact with food must be food safe, non-reactive, and resistant to low temperature and vacuum conditions.
- **Cycle time:** The freeze-drying process must be completed within a reasonable time.

3.2 DESIGN SPECIFICATIONS

Performance

- The vacuum pressure should be maintained below 0.1-1mbar to optimize sublimation without damaging delicate materials.
- The system should use a vacuum pump capable of maintaining a low-pressure environment to ensure efficient moisture removal.
- Temperature in the vacuum chamber should be -40ºC or lower to freeze the product.

- The freeze dryer must be capable of handling materials with different moisture contents and densities, ensuring uniform drying across all products.

Energy Efficiency

- The refrigeration and vacuum systems must be optimized for power efficiency while maintaining performance.
- The chamber should be well insulated to reduce heat transfer and enhance energy efficiency.

Size

- The freeze dryer should fit within a small working space ensuring it is compact and space efficient.
- The design should allow easy integration into small-scale production environments or home use.

Material

- The material used for the chamber should be durable, able to resist corrosion and thermal efficient.
- Heat exchanger should be copper or aluminium for efficient cooling.

Cost

- The cheapest products without sacrificing quality should be used.
- Use second-hand components where practical.

Manufacturing feasibility

- Fabrication should be possible using standard welding and machining methods

Assembly

- The unit should be easy to assemble and disassemble with common tools.

Availability of components

- Components used should be readily available on the market.

Transport

- The unit should have handles for easy movement.

Ergonomic

- Easy access door with vacuum tight seal.
- Use of a removable tray system for easy loading and unloading.

Safety

- Overheating and overcurrent protection via thermal fuses and circuit breakers.

Durability

- Vacuum chamber must withstand repeated pressure cycles without deformation.
- Refrigeration compressor should be rated for continuous low temperature operation.

Drying Cycle Time

- The freeze dryer should complete one full cycle within 24 hours per batch for efficiency and productivity, balancing drying speed with energy consumption.

- Each cycle must follow a controlled process of freezing, primary drying and secondary drying.

Final Product

- The system should prevent over-drying, which could lead to excessive fragility or loss of texture.

3.3 LIMITATIONS

- **Limited Capacity**

  Due to its compact size, the mini freeze dryer can only process small batches at a time. This makes it less suitable for large-scale production or businesses requiring high output.

- **Limited Automation**

  The mini freeze dryer lacks advanced automation features, requiring manual adjustments for temperature, pressure, and cycle settings. This can make operation more labour-intensive compared to larger, fully automated models.

- **Slower Processing Time**

The smaller size and lower power of a mini freeze dryer often result in longer drying cycles. The reduced refrigeration and vacuum capacity can extend the time needed to fully remove moisture from the material.

- **Less Control Over Temperature and Pressure**

  Unlike industrial-grade freeze dryers, mini models may offer fewer options for fine-tuning temperature and pressure settings. This can limit the ability to optimize drying conditions for different types of materials, potentially affecting the final product quality.

3.4 CONCEPTUAL DESIGN

The freeze dryer's basic operation, system components, and general functionality are outlined in the conceptual design phase, which forms the basis for its development. To guarantee peak performance, important design factors like sublimation, vacuum pressure control, refrigeration, and heat transmission mechanisms are examined at this point. Finding a workable and effective design that satisfies the necessary capacity while striking a balance between cost, energy efficiency, ease of maintenance, and safety is the aim. To create an efficient and dependable freeze-drying system, this phase also entails assessing various design options, choosing suitable materials, and guaranteeing technical viability.

As follows are the concepts generated;

3.5 CONCEPT ONE

This freeze dryer is designed to be compact and space-efficient, roughly the size of a microwave, making it ideal for home use.

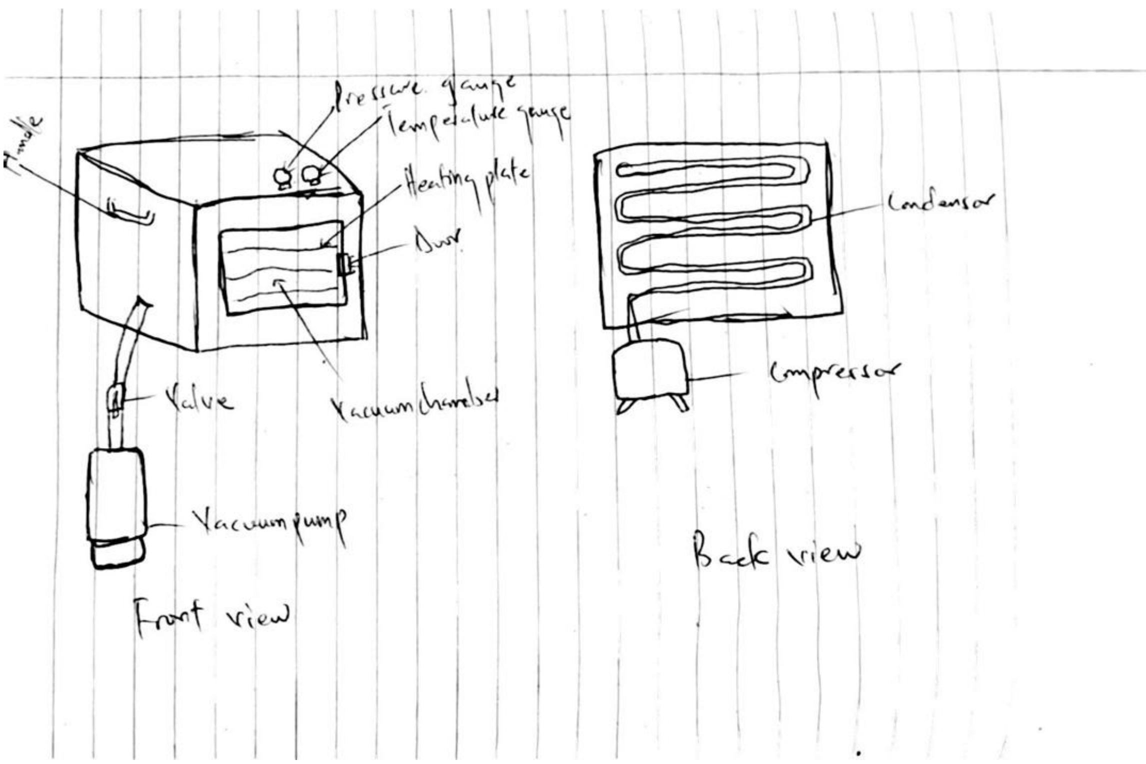


Figure 12 Concept One

COMPONENTS

Vacuum chamber

The main drying chamber is built with a stainless-steel interior, ensuring durability and resistance to corrosion, while the outer casing is made of aluminium, keeping the unit lightweight but strong. Between these layers, polyurethane foam insulation is incorporated to minimize heat transfer and enhance energy efficiency.

Inside the chamber, multiple trays rest on heated shelves, which gently provide warmth to facilitate the freeze-drying process. These shelves help ensure even drying by supplying controlled heat, allowing moisture to be removed gradually while preserving the texture and quality of the product. A temperature gauge, which monitors and displays chamber temperatures to ensure optimal freezing and drying conditions is placed outside the chamber. Also, a pressure gauge, which measures and regulates vacuum levels, ensuring the pressure stays within the ideal range for effective moisture removal.

Refrigeration System

The freeze dryer uses a 1.5 HP compressor to generate the low temperatures required for freezing. The refrigeration system includes a condenser, evaporator, expansion valve, and filter drier, all working together to bring the chamber temperature down to -40°C, preparing the material for the drying process. The condenser, compressor, expansion valve and filter drier are found at the rear end of the chamber while the evaporator is found inside the chamber.

Vacuum system

To remove moisture efficiently, the freeze dryer features an oil-sealed rotary vacuum pump, which creates a low-pressure environment. This vacuum allows ice in the product to sublimate directly into vapor without turning into liquid, ensuring that the food or material retains its original structure, flavour, and nutrients. A valve is placed between the vacuum chamber and pump to control the removal of air in the chamber.

With its well-insulated chamber, precise temperature control, and powerful vacuum system, this freeze dryer is designed to deliver high-quality, energy-efficient freeze drying in a user-friendly, compact package.

MODE OF OPERATION

- Place the product on trays inside the vacuum chamber and seal it tightly.
- Turn on the refrigeration system to freeze the product to -40°C.
- Once the product is completely frozen, turn on the vacuum system and maintain the refrigeration system simultaneously.
- The chamber pressure should be reduced to below 0.6 kPa. The refrigeration must remain on to prevent melting while water sublimates.
- Once most ice has sublimated, gradually apply heat through heating shelves to raise the temperature to around 30°C while maintaining a low vacuum. This removes the remaining bound moisture from the product.
- When the moisture content is sufficiently low, turn off the heating system and vacuum.
- Slowly allow air to enter the chamber before opening.

3.6 CONCEPT TWO

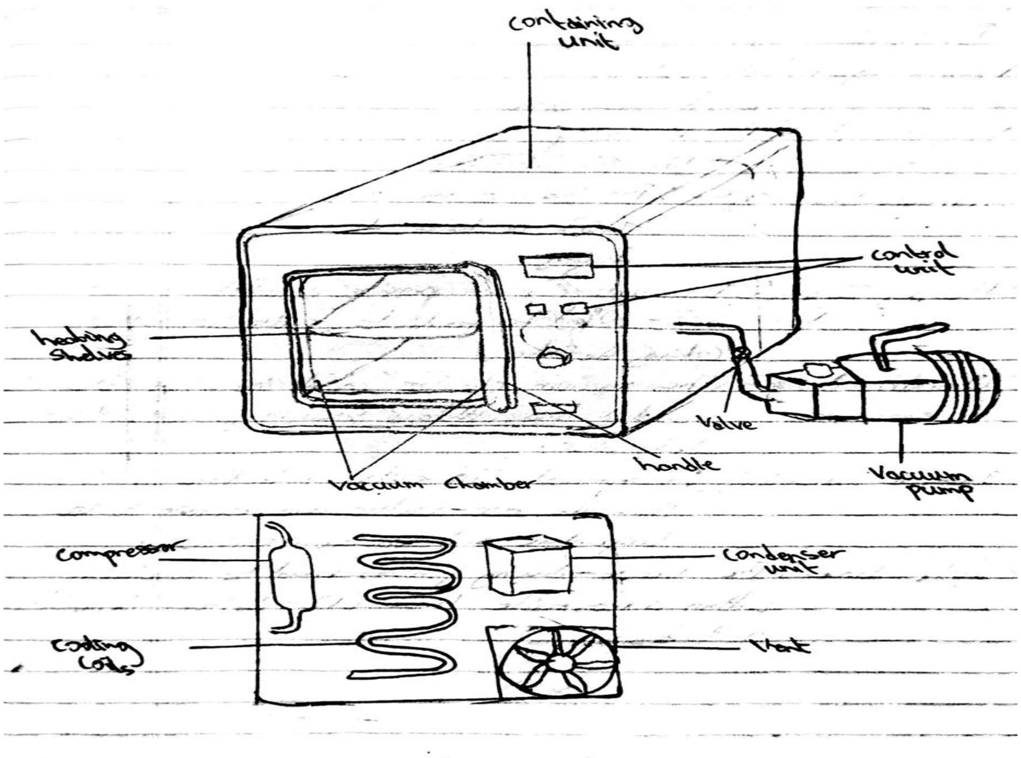


Figure 13 Concept two

This design is made up of a containing unit which is about the size of a microwave. Within the containing unit is the vacuum chamber which is airtight and has heating shelves for producing and evenly distributing heat from 30°C to 60 °C for the freeze-drying process. A vacuum pump is located outside the unit and its function is to remove air and water vapor from the vacuum chamber in order to reduce the pressure. There is a valve which controls the extraction of air between the vacuum chamber and the vacuum pump. The process is controlled by the control unit which allows the user to regulate certain parameters such as temperature. Behind the containing unit is the compressor which circulates the refrigerant within the system. The cooling coils cool the product inside the chamber. Located behind is also the condenser unit which rejects heat from the refrigeration cycle in conjunction with the vent.

HOW THE PROCESS OF FREEZE DRYING WORKS WITH THE DESIGN ABOVE

The product is placed into the chamber, the temperature is then lowered until the product is -40°C or lower. The vacuum pump is then turned on extracting all the air and moisture while reducing the pressure in the chamber. Once the pressure decreases, the temperature of the system slowly increases through the heating shelves. The warmer temperature and low pressure cause the ice crystals in the product to change from solid to gas (sublime), hence the product is freeze dried.

3.7 CONCEPT THREE

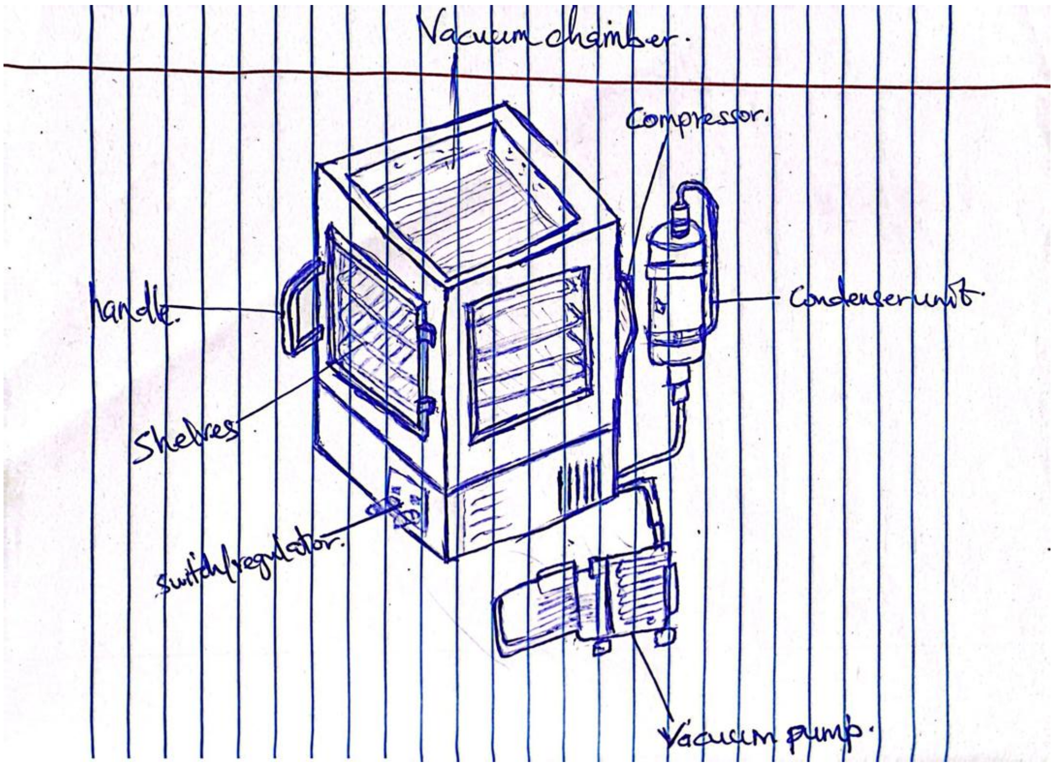


Figure 14 Concept three

The sketch shows a small batch-type mini freeze dryer with a control switch/regulator, front-opening door, shelving system, and vacuum chamber. The compressor and condenser unit manage refrigeration and moisture removal, while an external vacuum pump generates low pressure for sublimation. This design strikes a balance between usability and efficiency, making it perfect for small-scale freeze-drying.

MODE OF OPERATION

Freezing Stage: The product's water content is frozen by the refrigeration system cooling the chamber to between -30°C and -50°C. Evaporator coils absorb heat from the chamber, and the expansion valve controls the flow of refrigerant to guarantee quick cooling.

Vacuum Creation: By eliminating air, a vacuum pump lowers pressure to 10–100 Pa, enabling frozen water to sublimate straight into vapor rather than melting into liquid.

Primary Drying (Sublimation): While the vacuum is still operating, the heating system progressively rises the temperature from -40°C to 0°C, giving sufficient energy for sublimation. When ice transforms into vapor, the condenser coils catch it and freeze it to.

Secondary Drying (Desorption): To eliminate bonded moisture, the temperature is raised further from 0°C to 40°C. This lowers the final water content to 1-4 percent for long-term storage.

Packaging: The freeze-dried items are extracted and promptly sealed in airtight packaging to prevent moisture absorption.

3.8 EVALUATION CRITERIA TABLE

Parameter	**Evaluation Criteria**
Cost	-Cost of materials, components and operational cost.
Time to build	-Manufacturing and assembly time -component availability and lead times. -Time needed for testing and calibration.
Energy Efficiency	-Power consumption of vacuum pumps, refrigeration and heating. -Thermal efficiency in sublimation process.
Ease of maintenance	-How easy it is to clean vacuum chamber and heating trays. -Durability and longevity of parts.
Capacity	-Maximum batch size -Cycle duration and drying time efficiency.
Technical Feasibility	-Complexity of design and manufacturability. -Integration of vacuum, refrigeration and heating systems.
Material Selection	-Strength and durability under vacuum pressure and temperature fluctuations. -Corrosion resistance for long term use.

	-Compliance with food safety regulations.
Safety Considerations	-Vacuum chamber integrity to withstand pressure differentials. -Electrical safety -Emergency safety features (pressure relief valves, auto shut-off)

Table 1 Evaluation Criteria Table

3.9 DECISION MATRIX FOR CONCEPT SELECTION

Criteria	Weight (%)	Concept 1	Weighted Score	Concept 2	Weighted Score	Concept 3	Weighted Score	Comments

		(Score 1-10)		(Score 1-10)		(Score 1-10)		
Cost	15%	7	1.05	8	1.20	6	0.90	Concept 1 is the most affordable, but Concept 2 offers better value.
Time to Build	10%	8	0.80	7	0.70	6	0.60	Concept 1 is the fastest to build due to its simpler assembly.
Energy Efficiency	20%	7	1.40	9	1.80	6	1.20	Concept 2 has the best insulation and optimized

								energy use.
Ease of Maintenance	10%	5	0.50	8	0.80	7	0.70	Concept 2 has modular components, while Concept 3 is also fairly easy to maintain.
Capacity	15%	6	0.90	8	1.20	7	1.05	Concept 2 has the highest batch size, while Concept 3 is still competitive.

Technical Feasibility	10%	7	0.70	8	0.80	6	0.60	Concept 1 is easier to manufacture, but Concept 2 is more technically advanced.
Material Selection	10%	8	0.80	9	0.90	7	0.70	Concept 1 and Concept 2 use strong, durable materials.
Safety	10%	6	0.60	9	0.90	8	0.80	Concept 2 has superior safety features, but Concept 3 also has good

								structural integrity.
Total Score	100%	6.75		8.30		6.55		Concept 2 is the most balanced and efficient choice.
Total Score	100%	6.75		8.30		6.55		Concept 2 is the most balanced and efficient choice.

Table 2 Decision Matrix Table

3.10 CONCLUSION

While Concept 1 is the most cost-effective and fastest to build, and Concept 3 has some advantages in specific areas, Concept 2 remains the superior choice due to its energy efficiency, maintenance, capacity, and safety features.

3.11 FINAL CONCEPT

After evaluation, concept two was chosen as the final design among the three concepts developed.

3.12 DESCRIPTION OF THE FINAL CONCEPT

The selected design consists of a compact containing unit, approximately the size of a microwave, making it suitable for small-scale freeze-drying applications. Inside this unit is an airtight vacuum chamber equipped with heating shelves designed to generate and evenly distribute heat within a controlled temperature range of 30°C to 60°C. These shelves play a crucial role in facilitating the sublimation process by ensuring uniform heating of the product.

Externally positioned, the vacuum pump is responsible for extracting air and water vapor from the vacuum chamber, significantly lowering the internal pressure to create the necessary conditions for freeze-drying. A strategically placed valve regulates airflow between the vacuum chamber and the vacuum pump, allowing precise control over the pressure reduction process.

The entire operation is managed by a control unit, which provides users with the ability to regulate key parameters, including temperature and pressure settings, ensuring optimal drying conditions. At the rear of the containing unit, a compressor functions as the heart of the refrigeration system, circulating the refrigerant throughout the system to maintain the required low temperatures. The integrated cooling coils work to lower the temperature of the product inside the chamber, aiding in the freezing phase of the process.

Additionally, a condenser unit, located at the back, operates in conjunction with a ventilation system to effectively dissipate excess heat generated during the refrigeration cycle. This ensures the system remains efficient and prevents overheating. The overall design balances functionality and compactness, making it a practical solution for small-scale freeze-drying while offering precise control over critical parameters to optimize performance.

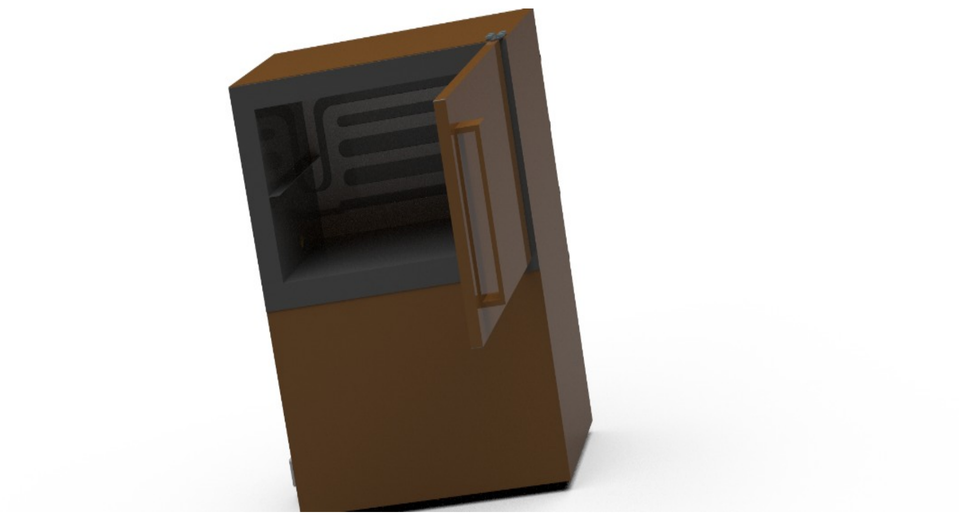


Figure 15   Final concept Design

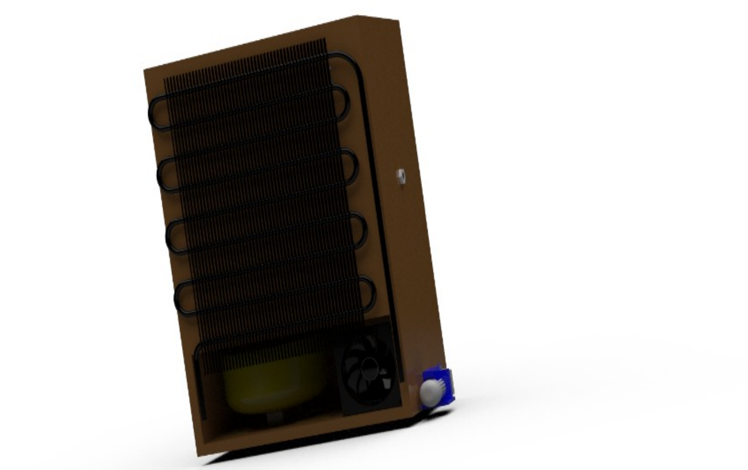


Figure 16   Final concept Design

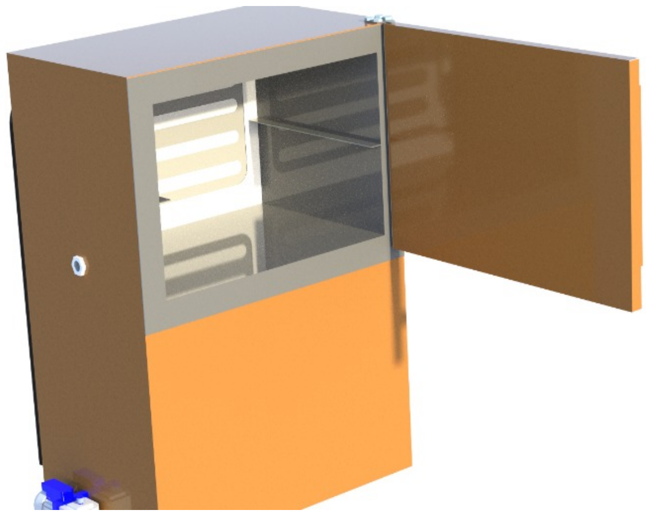


Figure 17   Final concept Design

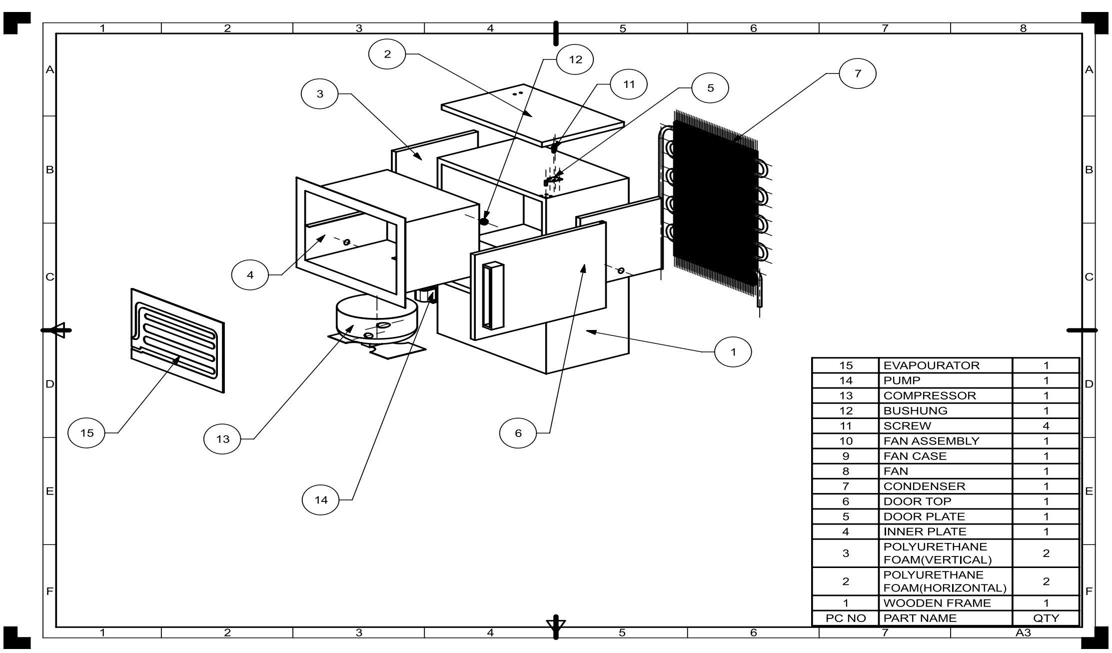


Figure 18 Final Concept

COMPONENTS

1. **Containing Unit**

- Houses and protects all internal components of the freeze dryer.
- Provides structural support and insulation for efficient operation.

2. **Vacuum Chamber**
    - An airtight compartment where the freeze-drying process occurs.
    - Maintains low pressure to facilitate sublimation (the transition of ice directly into vapor).

3. **Heating Shelves**
    - Generate and distribute heat evenly within the vacuum chamber.
    - Help raise the temperature of the frozen product to promote sublimation.
4. **Control Unit**
    - Allows the user to regulate and monitor key operating parameters such as temperature, pressure, and drying time.
    - Ensures optimal conditions for effective freeze-drying.
5. **Vacuum Pump**
    - Removes air and water vapor from the vacuum chamber to create a low-pressure environment.
    - Enables sublimation by reducing the boiling point of ice.
6. **Valve**

- Controls the extraction of air and moisture between the vacuum chamber and the vacuum pump.
- Helps maintain the desired pressure levels.

7. **Handle**
    - Used to open and close the vacuum chamber door securely.
    - Ensures an airtight seal when the chamber is in operation.
8. **Compressor**
    - Circulates refrigerant throughout the system.
    - Helps in lowering the temperature inside the chamber to freeze the product before sublimation begins.
9. **Cooling Coils**
    - Absorb heat from the vacuum chamber and lower its temperature.
    - Aid in freezing the product efficiently.
10. **Condenser Unit**
    - Captures and condenses water vapor removed from the chamber into ice.
    - Prevents moisture from re-entering the vacuum chamber.
11. **Vent**
    - Releases excess heat generated during the refrigeration cycle.
    - Helps maintain the efficiency of the system by preventing overheating.

4.0 CHAPTER FOUR- DESIGN CALCULATIONS AND DRAWINGS

4.1 DETAILED DESIGN CALCULATIONS

Design Specification

Parameter	Value
Product Load	1 kg of chicken breast
Initial Temperature	25°C
Freezing Temperature	-40°C
Vacuum Pressure	0.6 kPa (600 Pa)
Drying Time	5 hours
Refrigerant	R410A
Insulation	Vacuum panels + PU foam ($U = 0.2$ $W/m^2 \cdot K$)
Chamber Dimensions	350 mm × 500 mm × 300 mm
Ambient Temperature	25°C

Step 1: Cooling Load Calculation

Freezing Load

What we're solving for: Total energy required to freeze 1 kg of food from 25°C to -40°C.

Formulas Used:

- Sensible Cooling: $Q = m \cdot cp \cdot \Delta T$
- Latent Heat: $Q = m \cdot h\_fus$

Parameters:

- $m = 1$ kg

- cp (fresh) = 3.0 kJ/kg·K
- cp (frozen) = 1.8 kJ/kg·K
- h_fus = 333 kJ/kg
- ΔT1 = 25°C, ΔT2 = 40°C

Calculations:
- From 25°C → 0°C: Q1 = 1 × 3.0 × 25 = 75.0 kJ
- Phase change: Q2 = 1 × 333 = 333.0 kJ
- From 0°C → -40°C: Q3 = 1 × 1.8 × 40 = 72.0 kJ

Total Freezing Load: Q_freeze = 480.0 kJ

Average Freezing Power: P_freeze = 133 W

Sublimation Load (Adjusted to 5 Hours)
What we're solving for: Energy required to sublimate 0.75 kg of water in 5 hours.

Formulas:
- $\dot{m}$_water = m_water / t
- Q = $\dot{m}$ × h_sub

Parameters:
- m_water = 0.75 kg
- t = 5 × 3600 = 18000 s
- h_sub = 2840 kJ/kg

Calculations:
- $\dot{m} = 4.17 \times 10^{-5}$ kg/s
- Q_subl = 118.4 W

1.2 Heat Leakage
Formula: Q = U × A ×
ΔT

Parameters:
- U = 0.2 $W/m^2 \cdot K$
- A = 0.605 m^2
- ΔT = 65°C

Q_leak = 7.87 W

Total Cooling Load: Q_total = 259.27 W

Step 2: Refrigeration Cycle (R410A)

Refrigeration Effect per kg: q_evap = h1 - h4 = 178.0 kJ/kg
Compressor Work: w_comp = h2 - h1 = 72.3 kJ/kg
Mass Flow Rate: $\dot{m}$_ref = Q_total / (q_evap × 1000) = 0.00146 kg/s
Compressor Power: P_comp = $\dot{m}$_ref × w_comp = 106 W

Volumetric Flow Rate: $V = \dot{m} \times v = 0.000321\ m^3/s$

R410A States:

1: Superheated vapor, -50°C, 338.0 kJ/kg
2: Compressed vapor, 75°C, 410.3 kJ/kg
3: Saturated liquid, 50°C, 160.0 kJ/kg
4: Throttled mixture, -55°C, 160.0 kJ/kg

Step 3: Key Component Specifications

Compressor: Hermetic, 106 W, R410A
Evaporator: Plate HX, 0.05 m^2, -45°C
Condenser: Finned-tube, 0.55 m^2, air-cooled
Vacuum Pump: Two-stage rotary vane, 0.1 L/s @ 0.6 kPa
Expansion Valve: TXV for R410A, 0.2 kW
Cold Trap: Stainless steel coil, 0.1 m^2, -50°C
Insulation: Vacuum panels + PU foam (0.2 $W/m^2{\cdot}K$)

Final Design Summary (5-Hour Drying Time)

Cooling Capacity: 259 W
Compressor Power: 106 W
Water Removal Rate: 0.75
kg/5h
Chamber Dimensions: 350 × 500 × 300 mm
Weight: ≈16 kg
Power Supply: 100–240 V AC, 300 W max

Based on Updated Parameters from 5-Hour Freeze Dryer Calculations

1. Evaporator Size Calculation

Objective: To calculate the required surface area of the evaporator to absorb the total cooling load of 259.27 W at the evaporator's operating temperature of –45°C.

Formula Used:
$Q = U \times A \times \Delta T \Rightarrow A = Q / (U \times \Delta T)$

Given Parameters:

- Cooling Load (Q) = 259.27 W

- Overall Heat Transfer Coefficient (U) = 250 $W/m^2 \cdot K$

- ΔT = 10°C (from evaporator temp –45°C to product temp –

35°C) Calculation:

$A = 259.27 / (250 \times 10) = 0.1037\ m^2$
Recommended Evaporator Area:

$A_{evap} \approx 0.10\ m^2$

2. Condenser Size Calculation

Objective: To calculate the required condenser area to reject both the cooling load and the compressor work to the ambient air.

Formula Used:

$Q = U \times A \times \Delta T \Rightarrow A = Q / (U \times \Delta T)$

Given Parameters:

- Total Heat Rejection (Q) = 259.27 + 106 = 365.27 W

- Overall Heat Transfer Coefficient (U) = 300 $W/m^2 \cdot K$

- ΔT = 25°C (from 50°C condenser to 25°C ambient)

Calculation:
$A = 365.27 / (300 \times 25) = 0.0487\ m^2$

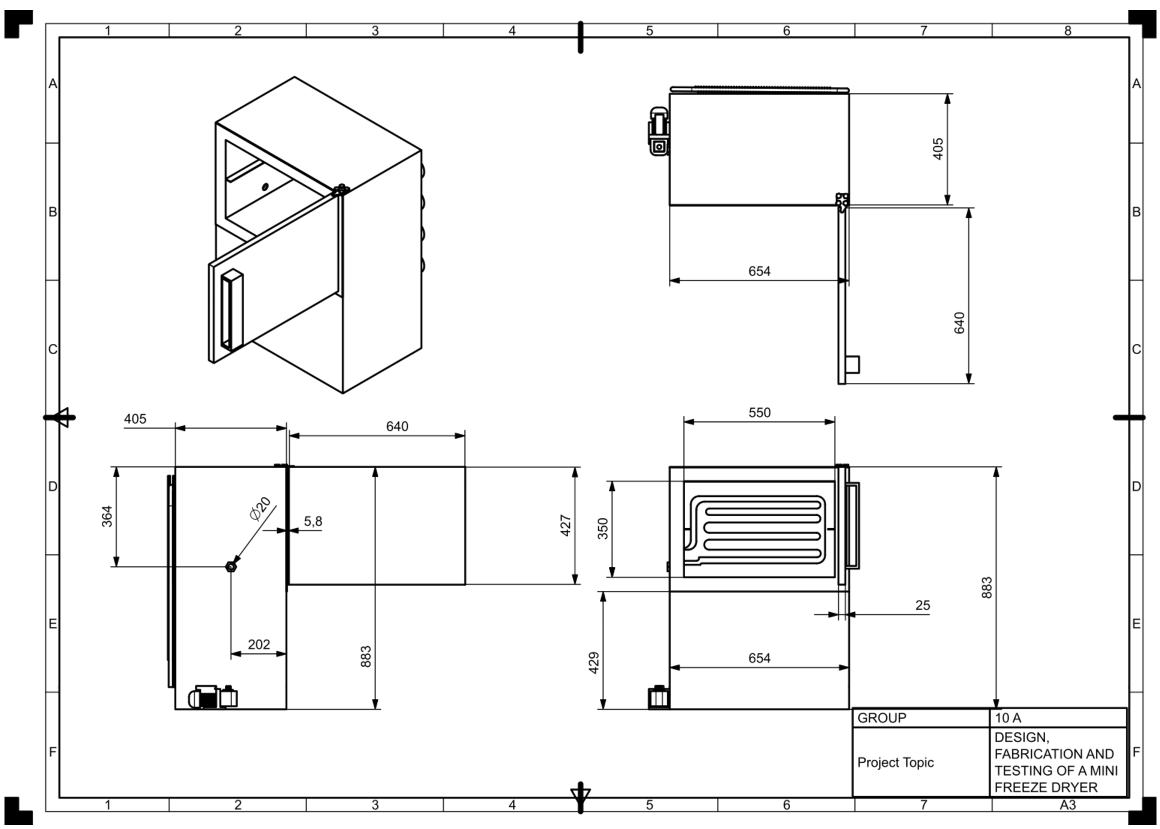
Recommended Condenser Area:
$A_{cond} \approx 0.5 – 0.6\ m^2$ (oversized for efficiency)

Final Component Summary (5-Hour System)

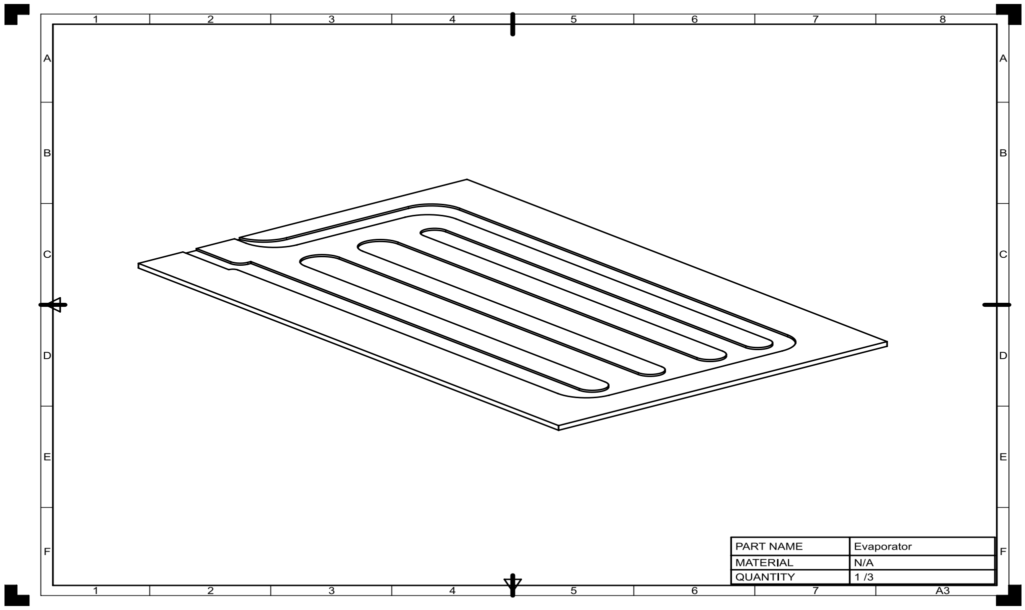
Component	Heat Load (W)	Temp Range (°C)	Area Calculated (m^2)	Recommended Area (m^2)
Evaporator	259.27	–45 to –35	0.1037	0.10
Condenser	365.27	50 to 25	0.0487	0.50– 0.60

4.2DESIGN DRAWINGS AND SCHEMATICS

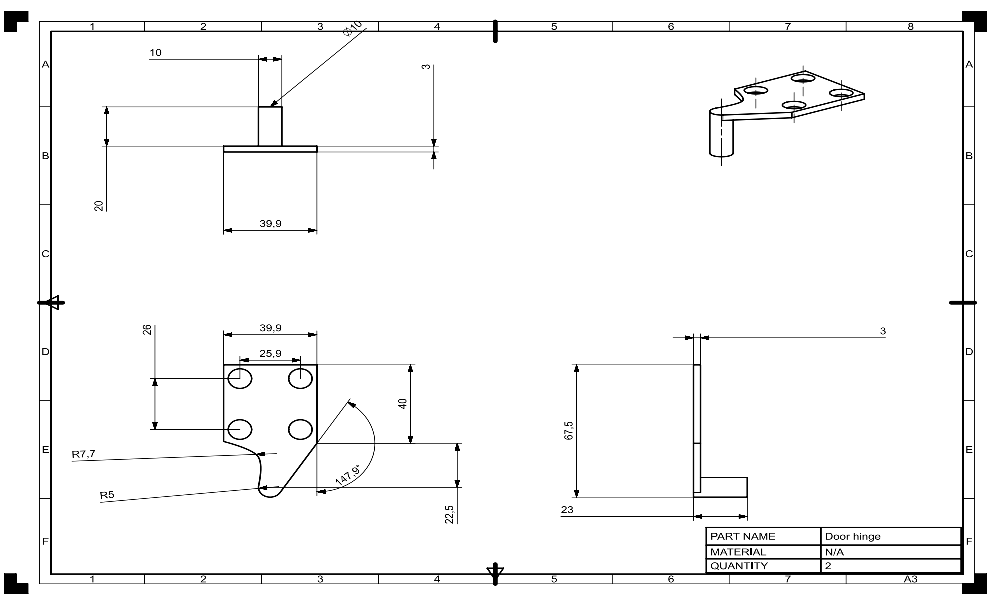
1) Detailed design



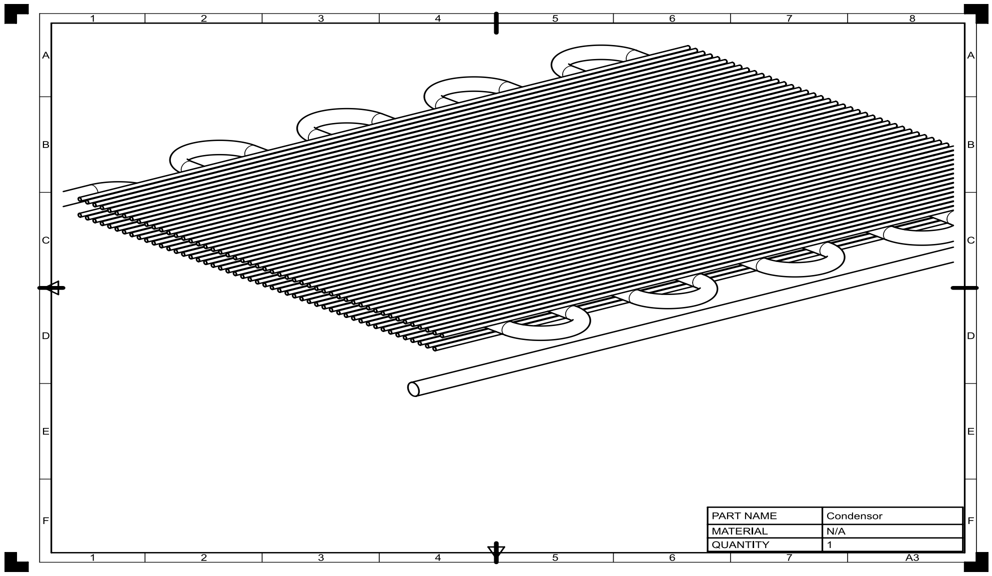
2)Evaporator



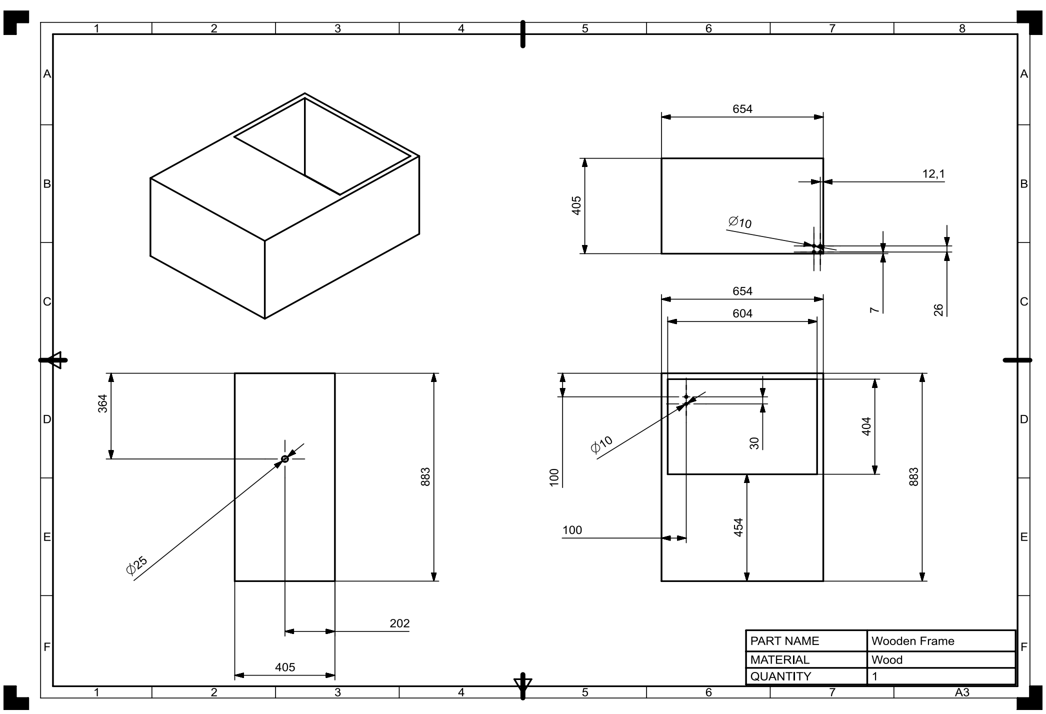
3)Door Hinge



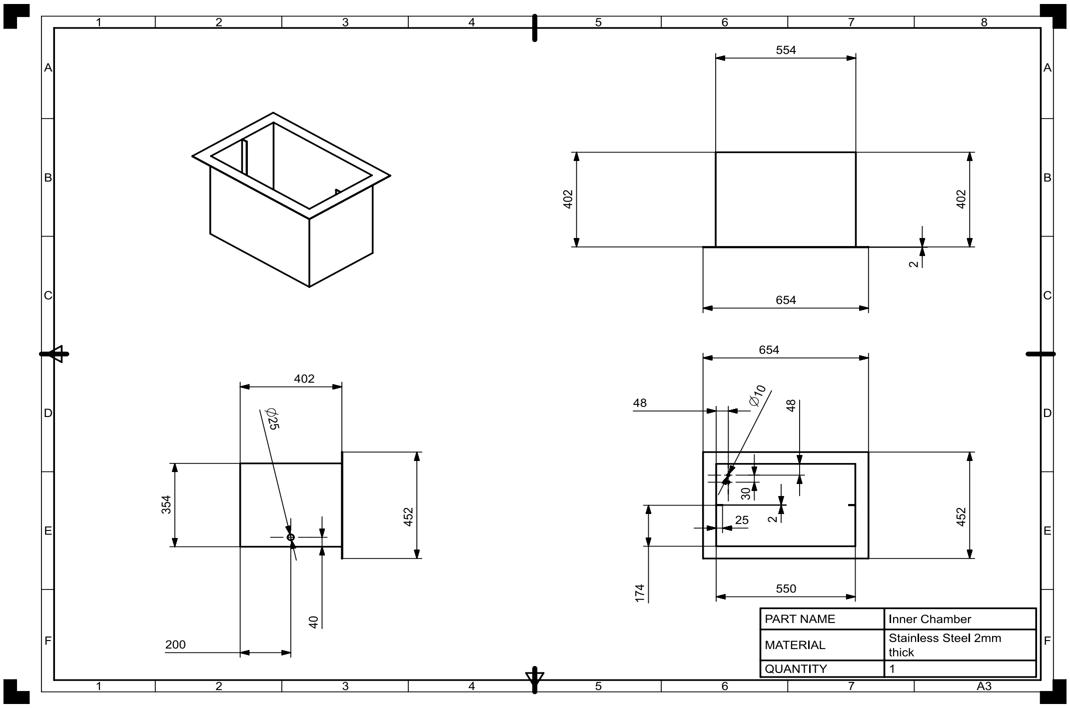
3)Condenser



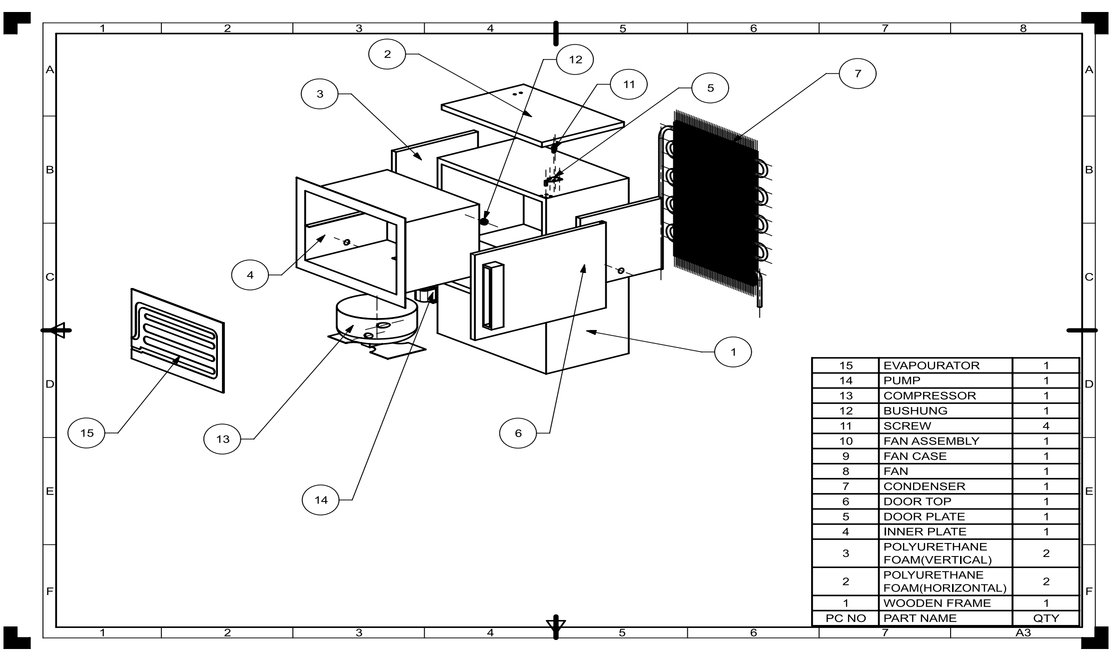
4) Wooden Frame



5)Inner Plate

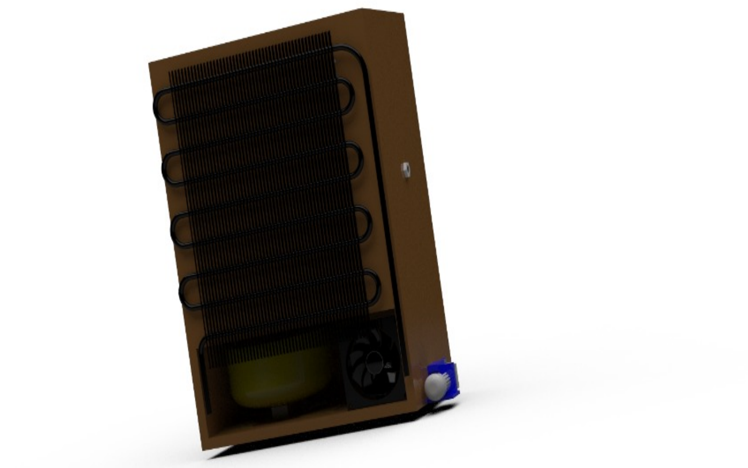


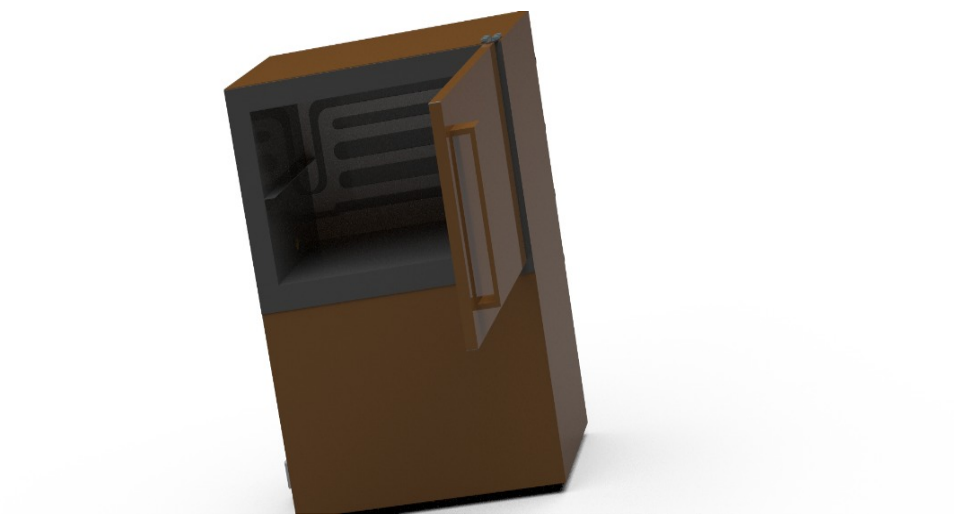
6)Explosion View

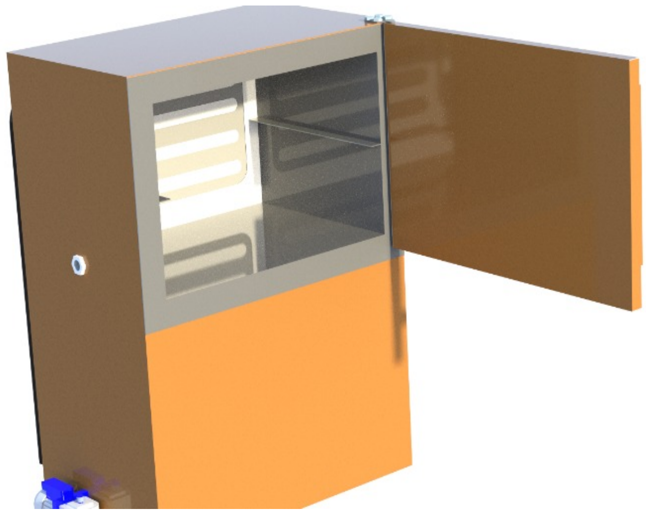


PC NO	PART NAME	QTY
15	EVAPOURATOR	1
14	PUMP	1
13	COMPRESSOR	1
12	BUSHUNG	1
11	SCREW	4
10	FAN ASSEMBLY	1
9	FAN CASE	1
8	FAN	1
7	CONDENSER	1
6	DOOR TOP	1
5	DOOR PLATE	1
4	INNER PLATE	1
3	POLYURETHANE FOAM(VERTICAL)	2
2	POLYURETHANE FOAM(HORIZONTAL)	2
1	WOODEN FRAME	1

7) CAD Model







CHAPTER 5

5.1 Fabrication and Assembly

Fabrication Processes and Equipment used

The fabrication of the freeze dryer was done using basic hand tools and readily available materials. The processes were selected based on affordability, ease of use and effectiveness in achieving desired functionality. The following processes were involved.

- Cutting of aluminum sheet.

  Hand shears were used to cut aluminum sheets to size. These sheets were used as the inner drying chamber for better hygiene and thermal conductivity.

- Outer chamber construction.

  The outer structure of the freeze dryer was made of plywood. The wooden parts were secured together using nails and screws. To improve appearance and provide a smooth, easy to clean surface, formica board was bonded onto the plywood using contact glue.

- Drilling and fitting.

  A hand drill was used to make holes in the aluminum and plywood for mounting components like vacuum pipe, fittings, refrigeration holes and electrical components.

- Welding of refrigeration components.

  The copper tubing and refrigeration component (compressor, evaporator and condenser) were joined using brazing to ensure leak tight refrigeration lines.

- Heating element fabrication.

  The heating system was created using resistive wire, which was arranged beneath the shelf. The connections were properly insulated and the terminals were added for safe wiring to a control unit.

- Sealing.

  Silicone sealant was applied to joints, pipe penetrations and chamber openings to ensure airtightness and vacuum integrity.

Tools and materials used

The tools and materials used are as follows.

- Hand shears
- Hand drill
- Hammer
- Nails
- Screws, Bolts and nuts

- Screwdriver
- Measuring tape
- Marker
- Contact glue
- Silicone sealant
- Plywood and formica board
- Aluminum sheet
- Brazing torch and filler rod
- Temperature gauge with thermocouple
- Contactor
- Electric wires
- Compressor (1/6 HP, R600a)
- Condenser (1/6 HP)
- Evaporator (1/6 HP)
- Vacuum pump
- Vacuum hose
- Pipe fittings

5.2 ASSEMBLY PROCEDURES

The assembly of the freeze dryer followed a step-by-step process, beginning with the internal chamber and progressing to the installation of major systems. The procedures ensured proper alignment, insulation, and airtight sealing of all components.

- Inner Aluminum Chamber Assembly:

The first step involved assembling the inner chamber using pre-cut aluminum sheets. The sheets were joined using screws and sealed at the edges with silicone to ensure an airtight enclosure suitable for food contact.

- Insulation of Inner Chamber:

Once the aluminum chamber was complete, polyurethane foam insulation was applied around all sides. This helped to minimize heat gain and support the freeze-drying process by maintaining low internal temperatures.

- Outer Wooden Chamber Construction:

The outer shell was built from plywood panels and assembled around the insulated aluminum chamber. Formica board was glued to the outer plywood surface using contact glue to provide a durable and smooth finish. Screws and nails were used for structural support.

- Refrigeration System Assembly:

After the chamber construction, the refrigeration system was assembled. The compressor, condenser, and evaporator were mounted in position. Copper pipes were brazed to connect these components, forming a closed refrigeration loop. Leak testing was performed after brazing.

- Vacuum System Connection:

The vacuum pump was installed and connected to the chamber through a vacuum-rated hose. A vacuum port was sealed into the chamber wall, and all fittings were secured and checked for leaks using silicone sealant.

- Heating System Installation:

The heating element, made using resistive wire (nichrome), was mounted beneath or around the product shelf area inside the chamber. The wire was supported on insulating material and connected to a thermostat. All electrical connections were insulated and wired to the control panel.

- Final Checks and Sealing:

All mechanical and electrical connections were inspected. Seals around pipes, doors, and ports were checked for airtightness. The system was then cleaned and made ready for testing.

CHAPTER 6-CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

This project successfully achieved its aim of designing, fabricating, and testing a mini freeze dryer tailored for small-scale food preservation, specifically focusing on perishable items such as meat and apples. Through a structured methodology that involved literature review, conceptual design development, component selection, detailed calculations, and physical fabrication, the team was able to construct a compact, functional freeze dryer that meets the needs of individual users and small food processors.

Recommendations

To further enhance the freeze dryer, the following recommendations are proposed:

- **Automation and Controls**: Integrating a programmable microcontroller or PLC for automated control of temperature, pressure, and drying cycles would improve consistency and ease of use.
- **Improved Instrumentation**: Incorporating more accurate sensors for real-time monitoring of chamber conditions can improve process reliability.
- **Modular Design**: Designing the system for scalability and modular expansion would increase its applicability for larger-scale operations.
- **Energy Optimization**: Exploring alternative refrigerants, enhanced insulation, or heat recovery systems could further reduce energy usage.
- **Enhanced User Interface**: Adding a digital display and user-friendly interface would simplify operation and make the system more accessible to non-technical users.

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