REFRIGERATION LOAD CALCULATION OF COLD STORAGE BOX USED FOR TOMATO STORAGE.

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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<u>**THESIS ACCEPTANCE CERTIFICATE**</u>

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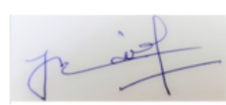
Signature (DEAN): 

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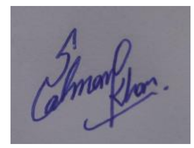

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DEDICATION

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

C_p	Specific Heat
h_{latent}	Latent Heat
$\dot{Q}_{respiration}$	Respiration heat
$Q_{Transmission}$	Transmission Load
U	Overall heat transfer coefficient
R_{Total}	Total heat transfer resistance
$\dot{m}_{air}$	Mass flow rate of air
ACH	Air change per hour
h	Enthalpy of air
ω	humidity ratio of air

ABSTRACT

Food loss and waste is a global problem, approximately 40 to 50% of fruits and vegetables are lost annually, exceeding 1.3 billion tons of food globally, with an estimated 750 billion US dollars wasted yearly. Throughout the stages of cultivation, handling, post-harvest, storing, processing, distribution, and consumption, food is lost. A smart cold storage and reefer container is a sophisticated thermal and relative humidity control system designed to preserve and effectively use perishable food products. Due to no proper post-harvest and transportation management, we are not losing the quantity, but we are also affected by losing nutritional quality of vegetables and fruits. The present study focused on reducing post-harvest loss of fruits and vegetables, more specifically on tomatoes during storing and transportation by providing an energy efficient small size solar powered smart cold storage solution with real time remote control of temperature and relative humidity. Solar panels are installed on the roof and walls of cold storage boxes for power generation during peak hours and batteries are installed for backup during low solar hours. The cooling is achieved by Vapor compression cycle. The temperature and percent relative humidity are set by a mobile app and are controlled by microcontroller. The cold storage box can be placed in ambient and can also be fixed in a vehicle for transportation as reefer container. The cold storage box includes both hardware and software parts, this IoT based control system is tested on a 110 liters DC chest freezer. The modeling of the temperature and relative humidity distribution inside cold storage walls was done using computational fluid dynamics (CFD).

Keywords: Internet of things (IoT), Cold Storage, Reefer container, Post-harvest, Solar powered, Food insecurity, Refrigeration cycle and IoT based control.

CHAPTER 1:INTRODUCTION

1.1 Objective of Cooling Load Calculations:

The objective of cooling load calculations is to make sure that the equipment for cooling is designed or selected, meeting the purpose of maintaining the required conditions. We can find the cooing capacity that is required for a cold room or freezing room with Cooling load calculations. Cooling load is calculated for the right selection of components of vapor compression cycle. Cooling load is the calculation of power or watt that needs to be removed heat from a specific area to maintain specific temperature and humidity. We cannot preciously define each and every thing it may change uncertainly. We must calculate the maximum cooling load for our system for smooth working. Cold storage works on refrigeration cycle and maintains low temperature even in negative depend on the product [1].

1.2 Importance of Food Preservation:

Tomatoes are among the most consumed vegetables in Pakistan and are sensitive to post-harvest losses due to their perishability,[1] so tomatoes are considered to be stored in cold storage and cooling load is calculated considering tomatoes as storing product. Fruits and vegetables are essential food for human health and can be prevents from spoils and loss by using cold storage and reefer container facilities. Fruits and vegetables quickly start to decay after being harvested because they are cut off from their source of nutrition and water [2]. It can be saved from being lost by choosing the best equipment for refrigeration, selecting the best insulation material and by maintaining controlled low temperature and high humidity, which are different for different fruits and vegetables. Cold storage and reefer container facilities can benefit both farmers and consumers [3]. Research conducted on cold storage of tomato in cold chain logistics technology, analyzed that 5°C cold chain transportation is more suitable for long-distance transportation based on tomato product temperature, nutrients, and sensory evaluation [4]. Fresh fruits and vegetables are essential elements of any human diet because they are packed with the required nutrients, such vitamins, which the body is unable to produce on its own [5]. Increase in population causes an increase in the production of vegetables and fruits which requires appropriate storage facilities [5]. In Pakistan the total production of fruits and vegetables are nearly 13.764 million tons, out of which it is estimated that 35 to 40 percent of fruits and vegetables were wasted after harvesting [6]. A report presented by MINISTRY OF NATIONAL FOOD SECURITY & RESEARCH of Pakistan explains that currently Government is giving high priority to the development of agriculture as it plays a key role in national economy boosting and ensuring food and nutritional security. Almost 37.4% population of Pakistan is directly or indirectly engaged in farming. Pakistan's fruits and vegetables market is expected to expand at a CAGR of 7.30% from USD 8.51 billion in 2023 to USD 12.10 billion by 2028 [7]. Food loss and waste are major problems each year. Approximately 1.3 billion tons of food are lost worldwide, of which 40% to 50% of losses are of vegetables and fruits. These losses occur 54% due to production, post harvesting, storing and handling, 46% occurs in food supply and consumption which totally cause loss of US$750 billion. Due to which storing and distributing becomes major research area [8]. According to a report published by United Nations, NDRC mentioned that almost annually one-third of all food products is lost due to no proper food management and its value nearby dollar 8.3 billion [9]. Human body needs nutrients like minerals, vitamins, potassium and other bioactive compounds which are present in fruits and vegetables [10]. Vegetables and fruits are essential parts of a nutritious diet. Decreased nutrition of fruits and vegetables is associated with poor health and a higher chance of noncommunicable diseases (NCDs). In 2017, it was estimated that 3.9 million deaths globally could be linked to insufficient eating of fruits and vegetables [11]. However, a significant amount (25–50%) of fruits and vegetables are lost worldwide from farm to fork; these losses are called post-harvest losses [12]. Different methods are used for food preservation like heat processing, dehydration, chemical preservation, oils and spices, canning, pasteurization and refrigeration [13].

1.3 Cold Storage and Cold Storage Design:

As cold storage usually requires refrigeration, it functions more like a whole air conditioning system, using a cooling coil to bring ambient air down to a lower temperature before reintroducing it into the storage space. The particular conditions found in cold storage facilities depend on the qualities of the goods being kept there. It is critical in these conditions to maintain exact control over both temperature and relative humidity (RH). Three main parts make up a cold storage facility a product chamber, systems for cooling and air circulation in the chamber, and material handling apparatus for stacking and distributing goods as needed. Since developing an effective refrigeration and air conditioning system which is considered as the major component of cold storage. It is required for cooling and air circulation; these processes are very important. Keeping the correct size refrigeration unit are very important for required cooling and minimize power consumption.

1.3 Importance of Solar powered Cold storage and Reefer Container:

Between 2000 and 2023, the number of people worldwide without access to electricity decreased by more than half, reaching 746 million in the latter year [14]. A major barrier to this project is the significant amount of energy needed to power and operate a cold storage unit. In developed and developing countries, where a significant portion of the rural population lacks access to the grid energy, which is a major cause for concern [15]. Pakistan is a developing country where electricity shortfall exceeded 6,500 megawatts [16] in some reports 8,500 megawatts is mentioned [17], resulting in eight-hour power outages in rural areas and four to six hours in urban areas. The average Pakistani household's electricity bill typically takes up 15% to 20% of their income, but recently it exceeds to 100% to 200% [18]. However, the quick development of the cold chain and refrigerated storage facilities will unavoidably result in energy consumption, mainly via the use of electricity. Furthermore, about 5% of the world's electricity is used for refrigeration [19]. From this perspective, operating cold storage using alternative energy can be the perfect solution because it provides the double benefits of primary energy savings and decreased environmental threat [15]. Cold storage using natural sources for cooling is a sustainable and cheap cooling technique. However, natural source technique suffers from some limitations like temperature control, humidity control, storage space [20]. The cold storage helps to slow down the biological activities, growth of microorganism, reduce transpiration losses, control temperature and humidity etc [21].

cold storage is the only widely utilized technique for handling perishables in large quantities between production and marketing processing [22].

1.4 Background of Research

Tomatoes are among the most consumed vegetables in Pakistan and are sensitive to post-harvest losses due to their perishability. However, the country faces significant challenges in post-harvest loss, energy scarcity, and inefficiencies in food storage technology. Tailoring a cold storage solution specific to tomatoes addresses these issues, promoting sustainability, reducing waste, enhancing food security, and potentially boosting the national economy through better preservation of this key agricultural product. When it comes to its nutritional content and high biological activity in the human diet, it is the most popular vegetable.[23] The tomato is becoming more and more recognized as the most affordable source of antioxidants due to its abundance in the total polyphenol content, carotenoids, β-carotene and ascorbic acid.[24] Studies indicate that bioactive substances, like polyphenols, provide numerous physiological advantages related to the functions of the circulatory system, including their antioxidant, anti-inflammatory, blood vessel-relaxing, and capillary wall-stabilizing properties.[25]

The main goal of refrigeration is to maintain the food's safety and quality. Taste, look, texture, flavor, and nutritional value are all components of a product's quality. Some microorganisms can only be destroyed by freezing. In the case of unwrapped products, the design of cold storage and cold transportation must minimize radiation heat sources, maintain high moisture content and minimal air movement to prevent loss of moisture and maintain the minimum needed temperature.[26] Pakistan has traditionally maintained a somewhat expansive approach when it comes to cold storage, frequently using the same techniques for many fruit and vegetable varieties. In case of cold storage for mixed product to maintain product, temperature is challenging because each vegetable and fruit has different latent and specific heat values.[27] This one-size-fits-all method doesn't take into account the specific needs of each type of produce, like tomatoes, leading to ineffective cooling and unnecessary energy use. What's more, with energy being a big issue in Pakistan, there's a growing need for new solutions that don't rely so heavily on traditional power sources. That's where solar-powered refrigeration comes in, offering a more sustainable option that fits the country's energy goals.[28]

1.5 Scope

The project aims to address the global issues of food loss and waste, focusing specifically on the difficulties faced because of the spoilage of fruits and vegetables, especially tomatoes. The main goal is to reduce post-harvest losses by using practical techniques, with a specific focus on cold storage and reefer container facilities. In order to proactively address energy consumption concerns, the project aims to utilize alternative solar energy sources to power these facilities. Furthermore, the project's focus on real-time cold storage box monitoring improves operational effectiveness, guaranteeing product quality, legal compliance, and risk reduction.

1.6 Problem statement

A major challenge is the wide global problem of food loss and waste, which accounts for around one-third of the world's annual production of food. In this context, fruits and vegetables account for 40–50% of the overall losses, or USD 750 billion, that occur each year. 54% of this waste occurs during storage, and 46% occurs during processing, distribution, and consumption. The waste is spread throughout multiple stages. Considering the nutritional value of fresh produce, especially tomatoes, which are known for their antioxidant capabilities. Improper handling and storage practices lead to a reduction in nutrition, which affects general health. Tomatoes also require cold storage due to their perishable nature, but this presents difficulties due to the significant energy needs of these facilities, particularly in areas like Pakistan that are experiencing an energy crisis.

The research problem is on the need for sustainable and energy-efficient cold storage solutions to reduce post-harvest losses, maintain nutritional quality, and solve energy consumption issues in areas with electricity shortages. In order to improve food preservation, reduce environmental effects, and solve energy accessibility concerns in developing nations, the objective is to investigate alternative energy sources, particularly solar energy, for cold storage unit power. The goal of the project is to address the needs of food preservation and storage while reducing energy use and environmental impact by helping to construct efficient and sustainable cold chain and refrigerated storage facilities.

1.7 Aims and Objectives of Innovation

- To minimize the fruit and vegetable losses after harvesting and during transportation.
- To determine the specific cooling load requirements for tomatoes based on their unique storage needs, considering factors like temperature, humidity, latent heat and specific heat.
- To develop an optimized and energy-efficient solar powered model for cold storage of tomato in Pakistan.
- To evaluate the model's impact on reducing post-harvest losses and its implications for food security and economic stability.
- To design an energy-efficient model of a refrigeration system that maintains the quality of tomatoes during storage.
- To compare the proposed model with traditional refrigeration methods in terms of cost, energy consumption, and preservation of tomato quality.
- Stabilizing the supply chain, benefiting both consumers, who face price fluctuations, and farmers, who suffer financial losses from spoiled crops.

1.8 Research Motivation:

Due to high loses (40% to 50%) of vegetables and fruits the storing and distributing becomes major research area [8]. Below are the SDGs which can be covered with cold storage and distributing facilities.

1.1. **No Poverty (SDG 01):** Nearly 45% of the world population lives in households where the head of the household works mostly in agriculture [29]. Cold storages and distribution can address SDG 1, No Poverty by the development of agriculture as it plays a key role in national economy boosting and ensuring food and nutritional security which will help job creation, stabilizing prices of food product and incomes of farmers.

1.2. **Zero Hunger (SDG 02):** In 2021, 9.5 billion tons of primary agricultural produce were produced worldwide [30], out of which approximately 35 to 40 percent of fruits and vegetables went to waste after harvesting [6]. The aim of the cold storage is to enhance food security through reducing the post-harvest and distribution losses, we can also preserve the nutritional quality of fruits and vegetables. The cold storage will help to promote sustainable agriculture.

1.3. **Good Health and Well Being (SDG 03):** Human body needs nutrients like minerals, vitamins, potassium and other bioactive compounds which are present in fruits and vegetables [10]. Vegetables and fruits are essential parts of a nutritious diet. The cold storage not only keeps the quantity for long time but also keeps the quality of food.

1.4. **Affordable and Clean Energy (SDG 07):** Solar energy is used as the energy source for cold storage. The solar energy is free, affordable, reliable, sustainable, available in abundant amount, available worldwide, cheap energy source, can't create any pollution and is the source of renewable energy.

1.5. **Decent Work and Economic Growth (SDG 08):** The solar powered cold storage supports sustainable economic growth by providing energy-efficient methods of storing agricultural products and by reducing post-harvest losses. It can also create jobs, empowering rural areas and provide independence from other sources of energy.

1.6. **Industry, Innovation and infrastructure (SDG 09):** The solar powered IoT based cold storage provides Energy Efficiency, Promoting Innovation, sustainable commercialization, sustainable agriculture**,** reducing greenhouse gas emissions, improving rural infrastructure, encourage investment in sustainable technologies.

The solar powered IoT based cold storage also cover Gender Equality (SDG 5) by providing Empowering Women in Agriculture and by providing equal entrepreneurial opportunities, Food Security and Nutrition. It is also related to Sustainable Development Goal 12 (SDG 12) and sustainable Development Goal (SDG 11) by providing renewable energy, reducing reliance on conventional energy sources, Minimization of Post-Harvest Losses, enhancing transportation of food.

1.9 Storage Facilities

Increasing in the production of fruits and vegetables needs proper storage and distribution to minimize food losses. Storage of fruits and vegetables may be either temporary, short time or long time. Different storage facilities including both natural and artificial cold storages used for different produces. The natural operating storages keeps the produce without having any treatment and are used to store produces and let them ripen while the artificial storages are used to maintained required temperature and relative humidity and are categorized into four types: (1) mechanical or structural, (2) controlled atmosphere, (3) chemical, and (4) radiation.

1.8.1 Traditional Storage Methods:

1.8.1.1 Natural Storage:

To improve market prices and avoid extra storage expenses, vegetables such as potatoes, yams, sweet potatoes, and garlic are naturally stored underground prior to the rainy season.

1.8.1.2 Artificial Storage:

Beets, potatoes, onions, carrots, turnips, cabbages, parsnips, and sweet potatoes are all stored in underground pits or trenches. Till there is a need on the market, they are buried in soil and straw.

1.8.1.3 Ventilated Storage:

High humidity is maintained at 35–40°F (1.7–4.4°C) in soil-covered underground cellars with slanting roofs. This structure provides humidity control and makes handling, grading, and packaging easier for a variety of vegetables.

1.8.1.4 Ice-cooled storage for refrigeration:

Ice is utilized as a refrigerant for extended storage of meat and perishables, which is an improvement over ground warehouses. Ice from ponds and lakes that have frozen over allows for longer storage. A major development in fruit and vegetable storage was made using ice boxes, a small-scale commercial and household device.

1.8.2 Modern Storage Methods:

Mechanical Refrigeration and Freezing of Foods are considered as modern storage systems. Perishable fruits and vegetables that are out of their harvest season can be marketed with the help of refrigeration most fruits and vegetables are available to consumers throughout the year. The freezing and refrigeration of perishable food items is a significant and fascinating use of thermodynamics and heat transfer. Refrigeration reduces the rate of food deterioration and quality loss by slowing down the chemical and biological processes in food. Fresh perishable items, like meats, seafood, fruits, and vegetables, have a shelf life that can be prolonged by a few days under refrigeration and up to several weeks or months under freezing. There are two types of vapor compression cycles.

1. Vapor Compression Refrigeration System (VCRS)
2. Vapor Absorption Refrigeration System (VARS)

1.8.2.1 Vapor Compression Refrigeration System (VCRS)

Mostly the cooling in cold storages is achieved by Vapor compression cycle are known as refrigeration cycle. In order to effectively remove heat from the storage compartment, the refrigerant goes via an expansion valve, where its pressure drops and the liquid evaporates at low enough temperatures. The fruits and vegetables that need to be cooled generate the heat required for evaporation. The storage area contains the evaporator. The compressor repressurizes the increase the temperature of refrigerant gas, which is subsequently sent through a condenser to cool it down to a liquid. The condenser, which rejects heat, is situated outside the storage space. Expansion valve or capillary tube reduces its pressure and temperature, causing it liquid-vapor mixture. To achieve a necessary or desired cooling temperature, refrigerant is metered out and stored in the receiver.

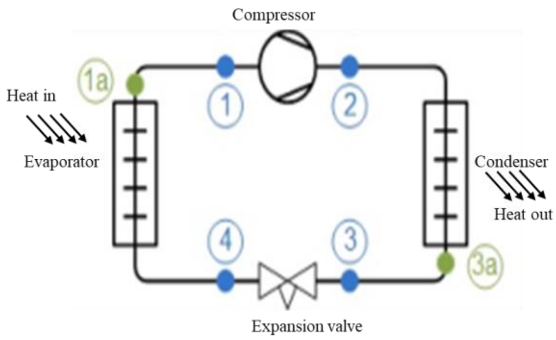

Figure 1. 1: Vapor Compression cycle

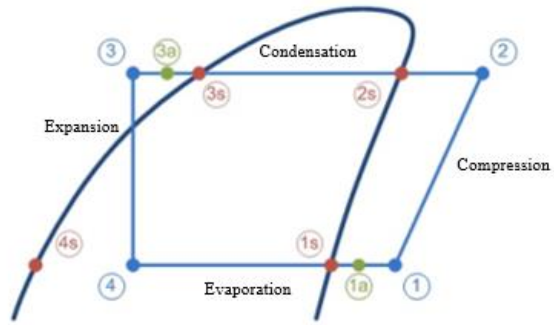

Figure 1. 2: Ph diagram for refrigeration cycle

1.8.2.2 Vapor Absorption Refrigeration System (VARS)

In a Vapor Absorption Refrigeration System (VARS) vapor from refrigerants are absorbed into an absorber solution after evaporation. Key parts of the basic VARS setup are the generator, absorber, pump, condenser, expansion device, and evaporator. The vapor absorption cycle works on using of an absorbent and refrigerant solution to absorb and release heat for cooling is how. The refrigerant is absorbed by the absorbent solution in the evaporator after it vaporizes due to heat absorption. Refrigerant that has vaporized is now contained in the solution; this causes the absorber to emit heat, which brings the refrigerant back to liquid. Restarting the cycle, the separated absorbent which now has a reduced refrigerant concentration returns to the evaporator. Because this heat-driven method doesn't require a mechanical compressor and is energy-efficient, it can be used in settings where waste heat or other low-quality heat sources are present.

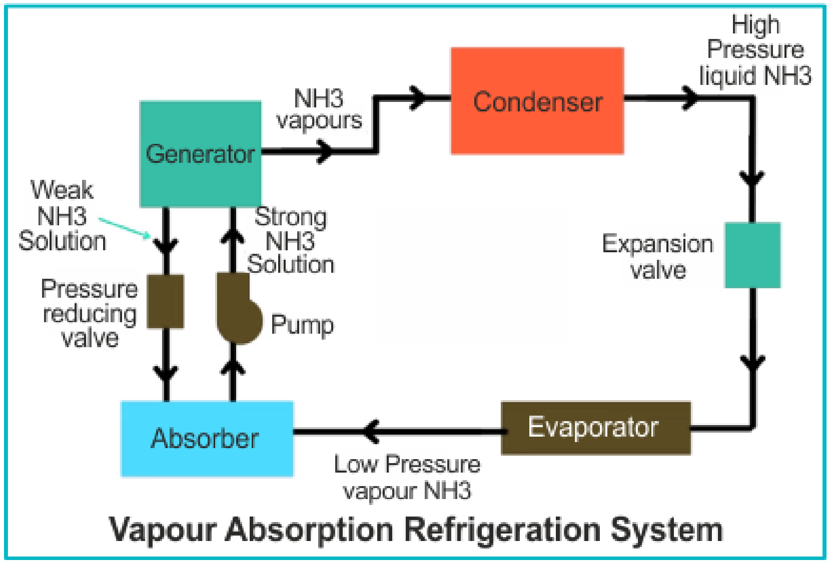

Figure 1. 3: Vapor Absorption Refrigeration System [31]

1.10 Temperature and Humidity Control:

Mechanical refrigerated storage depends on relative humidity, temperature and air movement that need to be controlled successfully.

1.9.1 Temperature

A tight, well-insulated construction and sufficient cooling capacity are necessary for maintaining the temperature. Additionally, the temperature depends on the amount and kind of evaporator-coil surface, the airflow rate over the coils and the ambient temperature. These factors control refrigeration's overall effectiveness. Different storage temperatures are recommended for different products. The correct sizing of equipments is so important to achieve the required temperature. The percentage of saturated water vapor at certain temperatures is known as relative humidity. The air ability to hold water increases with temperature. The air at the same relative humidity at 21°C contains significantly more water vapor as compared to air at 4°C. The air ability to remove water from moist produce increases when its vapor pressure decreases in combination with a decrease in relative humidity.

1.9.2 Relative Humidity

The percentage of saturated water vapor at a specific temperature is known as relative humidity. The ability of air to hold water increases with increase in temperature. As a result, air at 21°C with 90% RH contains significantly more water vapor as compared to air at 4°C. The ability of air to remove water from moist produce increases when its relative humidity decreases, so its vapor pressure also decreases Consequently, maintaining a high vapor pressure is important. The ability of air to remove water from moist produce increases when its relative humidity decreases, so its vapor pressure also decreases Consequently, maintaining a high vapor pressure is important. A slight vapor pressure difference between the stored produce and the storage air must be maintained if drying is to be avoided. Achieving this can be effectively done by quickly reducing the temperature of the produce and the air. keeping the relative humidity of the storage room air as high as the produce will tolerate, and the movement of air is not required for evenly distribution of temperature in the refrigerated room.

CHAPTER 2: LITERATURE REVIEW

Various studies have been carried out to determine the loads in different scenarios, such as transmission loads, infiltration loads, product loads, and equipment loads. Different environmental factors (ambient temperature, relative humidity, air speed), foods (Fruits and vegetables), insulation materials and sizes are considered according to their need. In much research work the heat transfer through convection and radiation are not considered because they have little heat load. In this paper convection, conduction and radiation mode of heat transfer is considered. We need efficient cold storage facilities for fruits and vegetables in agriculture to reduce losses after harvesting, especially in countries like Pakistan that have hot climates. This literature review explores various studies and their findings on cold storage solutions, specifically focusing on vegetables and the unique challenges and requirements they present.

2.1 Review of Research Work

This section has been divided into the following sub-sections.

2.1.1 Post-Harvest Losses in Agricultural Sector Pakistan's

Khurshid Ahmad and Nasir Ali Khan paper focuses on the issue of post-harvest losses in developing countries like Pakistan. These losses are a significant concern for food security and can lead to higher prices for agricultural products in the country. The authors of the paper delve into the main reasons behind post-harvest losses. These include factors like physical damage to crops, improper handling during storage and transportation, the presence of harmful microorganisms, a lack of modern technology, poor time management, and infestations by insects and mites. It also highlights the importance of reducing post-harvest losses as a main goal of the agricultural sector and suggesting that training and educational initiatives could be effective strategies for minimizing these losses. This work discusses the challenges faced in Pakistan's vegetable and fruit production, as well as the importance of implementing better strategies and policies to tackle these issues. It provides information on the significant losses that occur after harvesting fruits and vegetables in

Pakistan, covering various stages like collection, farming, retail, and wholesale and also highlights the factors that lead to these losses.[1]

2.1.2 Post-Harvest Losses and Shelf Life of Tomato in Lahore, Pakistan

Abdullah Farhan ul Haque Saeed and Salik Nawaz Khan present study which focused on the shelf life of tomatoes based on a systematic survey of the distribution of tomato crops in markets in the district of Lahore (Pakistan). It evaluated the post-harvest losses of tomatoes due to various factors such as storing, packing material, transportation system, and means of distribution. The research discovered that after crops are harvested, there can be significant losses, possibly reaching more than 30%. These losses are primarily caused by certain types of fungi, specifically Aspergillus niger, Aspergillus flavus, Fusarium oxysporum, Rhizopus stolonifer, and Aspergillus fumigatus, which contribute to the spoilage of the harvested crops. The study emphasized the importance of conducting a thorough and in-depth survey to develop effective strategies for minimizing these losses caused by fungi. This is essential not only because it has a negative economic impact but also because it affects the availability of food in the supply chain.

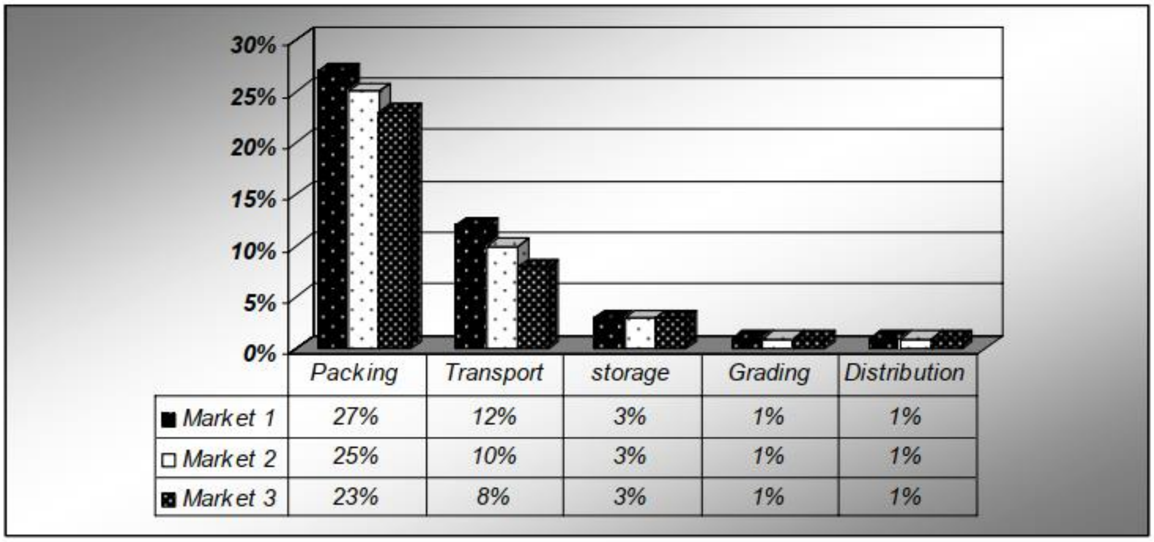

Figure 2. 1: Post-Harvest Losses of Tomatoes due to various factors

Some other important sources of information on this topic include research studies about plastic films that can be eaten and break down naturally, data about farming in Pakistan, and the work being done by a team in Nigeria that is working together on making better packaging and storage methods for fruits and vegetables.[32]

2.1.3 Tomato Shelf Life Enhancing through refrigeration.

Larissa R. de Castro and Luís A. B. Cortez conducted a study to see how sorting, refrigeration, and packaging impact how long tomatoes can stay fresh. They discovered that when tomatoes are stored at higher temperatures, they become sweeter but also lose more weight and become less firm after being stored for 9 days. The study compared tomatoes stored at 24°C for 9 days with those stored at 13°C for 22 days and found similar postharvest characteristics. Lower storage temperatures, such as 13°C, were found to improve the conservation of quality in tomatoes, including coloration, firmness, pH, sweetness, sourness, and weight loss. Sorting and packaging factors were found to affect some isolated characteristics of tomatoes but did not strongly influence shelf life. Packaging is crucial when it comes to preserving the quality of tomatoes as they are transported and sold. It serves various purposes such as safeguarding the tomatoes from damage, allowing proper airflow and cooling, and being able to withstand different weather conditions. Carton boxes were recommended over wooden boxes due to their smoother surface, which minimizes injury incidence and contamination.[33]

2.1.4 Economic Outlook and Energy Potential in Pakistan

Salman Manzoor Pakistan is a semi-industrialized country with a presentable agriculture base, food processing textile, and a per capita GDP of 1561 USD. It is anticipated to act as a global energy and trade hallway in the forthcoming because of its strategic location. The broad difference between supply and demand for electricity in Pakistan was recorded as 26.82 in 2009-2010, which increased to 50 in the summer of 2012. However, the electricity supply has improved in recent years, with the capacity of equipped electricity production reaching 37,402 MW in 2020 but its expensive. Pakistan's current indigenous energy resources primarily comprise coal, gas, oil, and hydro. The research strategy used in the paper includes action research approaches, experimental research, surveys, interviews, and systematic literature review. The data analysis in the paper involved the use of quantitative research methods and the analysis of quantitative data through pie charts. This approach ensured the accuracy of the results and allowed for the visualization of large sets of data.[34]

2.1.5 Enhancing Food Security:

The paper discusses the creation and customization of a commercial cold storage facility for the Umudike community and its surroundings. Its main goal is to offer improved storage for perishable food items and raise the living standards of the residents. The study tackles the issue of inadequate cold storage options in Umudike, despite the area's high agricultural production and business activities. The cold room's design adheres to standard refrigeration principles and considers the local climate in Umudike. The paper includes design calculations and specifications, covering aspects like refrigeration capacity, operating temperature, and estimated expenses. This cold storage facility is anticipated to enhance the community's quality of life by providing access to fresh foods and dairy products, boosting the local economy through better preservation, and reducing the need for frequent farm visits during harvest.[35]

2.1.6 Designing a Cold Storage Facility for Seed Potatoes

Aye Tun focusing on the design of a cold storage facility tailored for seed potatoes, essential calculations were presented to determine the cooling load required. The ideal indoor environment was determined to be 20°C, with a relative humidity of 92% to optimally store seed potatoes. The heat load within this storage facility encompasses various factors: conduction of heat through walls and ceilings, the inherent heat of the product, respiration heat, the heat resulting from air changes, heat generated by occupants, and that from lighting. One pivotal element, the transmission heat, which specifically accounts for the heat conducted through the walls and ceiling, is calculated. The facility is designed to accommodate 2000 metric tons of seed potatoes. The proposed structure consists of multiple floors.[35]

2.1.7 Designing Energy-Efficient Cold Storage

Robert Kraemer and Andrew Plouff initial goal was to design an energy efficient cold storage unit that could store a wide range of produce at a reduced energy cost when compared to the existing refrigeration system. An energy-efficient cold storage unit is designed for the Student Organic Farm (SOF) to provide year-round pristine produce at a low energy cost. The work determined the dimensions of the cold storage rooms based on the maximum produce load and storage container requirements. A large room and a small room is designed for more efficient storage, with the ability to switch between cool and cold produce depending on the season. The total heat load of the unit is analyzed, considering factors such as field heat, respiration heat, conduction heat, and heat from electrical components and workers. Electricity cost and payback analysis is also done.[36]

2.1.8 Considerations for designing Cold Storage

T. Krishnakumar provides information about how to design cold storage facilities in a way that efficiently controls temperature. The paper covers various factors such as heat transfer coefficients, wall thickness, insulating materials, and thermal conductivity. It also stresses the importance of resistance to heat movement (known as the R-value) in insulation materials and the need to prevent moisture from getting inside cold storage warehouses.

The paper discusses the use of specialized brines for circulating brine systems at extremely low temperatures and the significance of considering ground loads for each project. Additionally, it highlights the importance of keeping the cold storage facility partially to fully stocked to avoid temperature fluctuations and the need for organized stock rotation. The work also points out that the accuracy of measuring instruments and the careful regulation of conditions inside the storage chamber are essential to maintain ideal storage conditions for frozen products. Lastly, the paper includes information about commonly used building and insulating materials along with their properties in the appendix.[37]

2.1.9 Significance and purposes of Food Storage

Farooq Khan and Sumati Narayan's paper discusses the reason we should store food and what benefits it brings. These include keeping crops fresh when they aren't in season, ensuring food stays tasty, slowing down the spoilage of food, protecting it from frost, making sure we always have enough to eat, avoiding situations where we have too much or too little food, and even getting better prices for our produce. In their paper, they introduce a simple and affordable way to keep food cool without using electricity. They call it "zero energy cool chambers" or ZECC for short. You can build these chambers using easy-to-find materials like bricks, sand, and bamboo. ZECC can lower the temperature inside by 10-15°C and keep the air moist, which helps fruits and vegetables last longer and stay fresher. The paper also emphasizes how important temperature is when it comes to storing food. The temperature can greatly affect how fast things change in food, like how it spoils or ripens. The authors point out that temperature is the most crucial factor in these changes, and even a small increase of 10°C can make a reaction happen 2 to 3 times faster.[38]

2.1.10 Recommendations for Improving Energy Efficiency in Cold Storages

Vipin Yadav's research focuses on providing fundamental information about cold storage facilities, with a particular emphasis on the Indian context. The research points out that many cold storage units in India are not performing well when it comes to their overall energy usage, energy auditing, and facility management. The paper discusses key considerations that should be taken into account during the planning, construction, and operation of cold storage units in order to reduce their overall energy consumption. It also provides technical details about energy-efficient refrigeration systems and explores the possibility of using alternative energy sources, such as solar power. The main deliverable of the research is that there is a need to enhance the energy efficiency of cold storage units and to incorporate renewable energy sources like solar power. To achieve this, the research suggests various measures, including better door management, automatic closing doors, improved control systems, efficient motors, and additional insulation.

Additionally, the paper mentions the presence of a Central Cold Storage Advisory Committee in India, which advises the government on matters related to cold storage regulation and industry development. It underscores the significance of operating cold storage facilities in an energy-efficient manner to achieve goals related to conserving electrical energy and reducing carbon dioxide emissions.[39]

2.1.11 Improving Food Safety and Energy Savings in Cold Storage

Pannita Chaitangjit research findings can benefit other cold storage and temperature-controlled truck users by enhancing cold chain efficiency, food safety, and energy cost-saving. This study focuses on the importance of maintaining the safety and quality of temperature-sensitive and perishable agricultural raw materials in the food service industry. The research aims to identify problems and suggest solutions for establishing proper cold storages with temperature controlled. The study utilizes in-depth interviews, temperature monitoring using infrared thermal cameras and data loggers, and causal loop diagrams to analyze the causes of inefficiency in the cold chain management. The study also highlights the decrease in temperature after closing the door, resulting in higher electricity costs, and identifies the door area as the most vulnerable location in terms of temperature control. This study also provides practical recommendations for improving the efficiency and safety of temperature-controlled transportation and storage.[40]

2.1.12 Tomato Ripening and Antioxidant Dynamics in Cold Storage

Mekhled Mutiran Alenazi This research focused on examining how the levels of natural antioxidants in tomatoes change as they ripen and how this affects their storage quality in cold storage. There are concerns about the use of artificial antioxidants due to their potential impact on human health and the environment. We found that the highest levels of hydrophilic antioxidants like ascorbic acid, phenolic compounds, and flavonoids were present when the tomatoes were in the 'pink' to 'light red' stages of ripeness. Conversely, 'red' stage tomatoes had the highest levels of lycopene and b-carotene. We also looked at how the tomatoes' taste and texture changed during storage. The goal of this study was to provide a foundation for producing tomato-based foods or food products with improved functional characteristics. We conducted the research using 'Red Rose' tomatoes grown in a greenhouse and analyzed the samples using reference compounds like gallic acid, quercetin, L-ascorbic acid, b-carotene, and glucose, along with the Folin-Ciocalteu (FC) reagent for the analysis of total phenolic content (TPC) in the fruit samples.[41]

2.2 Scope and Purpose

2.2.1. Cold Storage in Agriculture:

Food stays longer when it is kept at optimal temperature and humidity levels. It prevents spoilage and extends the shelf life of perishable products. Food spoils when bacteria grow on or in it. Cooling or freezing stops or slows down the growth of bacteria. The temperature range for refrigerating fresh food is different for different foods and is provided by ASHRAE. Cold storage provides custom solutions for different agricultural products.

2.2.2. Specific Needs for Tomato Storage:

Tomatoes are quite delicate and can spoil easily, so they need to be stored in a particular way to keep them fresh for as long as possible. To do this, it's important to keep them at a temperature between 4°C and 12°C and maintain a humidity level of 90-95%. These conditions are essential for extending the time you can store tomatoes without them going bad. Tomato is an Important vegetable and is produced worldwide. In a report published by the Planning Commission of Pakistan in 2020, it was noted that the trade imbalance related to tomatoes in the country has significantly increased over time. The trade deficit exhibited notable fluctuations throughout the 2010s, with noteworthy peaks in 2016 and 2017, but has consistently remained in the negative territory. In Pakistan, tomatoes are a vegetable crop with substantial economic significance. Over the previous five years, the nation's yearly tomato exports have generally averaged around 9832 tons.[42]

Table 2. 1: Area, Production and Yield of Tomatoes by Province of Pakistan [42]

Province /District	Area (000 ha)	Production (000 tonnes)	Yield (t/ha)	Share in area (%)	Share in production (%)
Punjab	8.1	105.6	13.0	13.4	18.6
Sindh	26.4	195.8	7.4	43.6	34.4
Khyber Pakhtunkhwa	13.4	127.6	9.5	22.1	22.4
Balochistan	12.6	140.0	11.1	20.8	24.6
Pakistan	60.5	569.0	9.4	100.0	100.0

2.2.3. Energy Considerations in Cold Storage

Considering the current energy production and expenses the cold storage is made energy efficient by providing solar powered cold storage solutions in Pakistan. The cold storage units can be made more energy efficient, such as better door discipline, proper insulation, automatic closing doors, improved control systems, DC power compressor, designing the whole system for DC power. Solar-powered refrigeration for agricultural storage found it to be a viable and sustainable option. Innovative technologies are becoming available that are completely changing how cold storage facilities save energy. These developments are a desirable alternative for companies across a range of industries since they not only solve environmental issues but also result in significant cost savings. We'll look at a few of the cutting-edge developments that are changing the cold storage market in this post.[43]

2.2.4. Economic Implications of Efficient Cold Storage

High amount of post-harvest losses of tomatoes in Pakistan is 25 to 40%. They underscored the importance of improving cold storage technology to stabilize market prices and improve economic returns for farmers.

2.2.5. Storage:

Without cold storage, it can be challenging to store tomatoes in tropical and subtropical regions. Fresh tomatoes intended for table service should not be kept in storage for a long period of time. When ripe, tomatoes are harvested and refrigerated for several days before being shipped to far-off markets. The tomatoes will ripen to a marketable stage during the journey. Export-oriented tomatoes are frequently shipped in sizable containers equipped with ethylene treatment units and cold storage capabilities. If tomatoes are stored below 10°C for more than two weeks, or at 5°C for more than six to eight days, they will begin to deteriorate.[42]

2.2.6. Tomato Refrigeration Methods and Quality

Traditional refrigeration methods can sometimes affect the quality of tomatoes. When it comes to storing tomatoes, it's important to choose a method that not only keeps them fresh but also preserves their taste and nutritional value. If the objective is to store tomatoes for up to a week or a maximum of two weeks, refrigeration is the best choice to maintain their flavor and texture. However, if you need to store tomatoes for an extended period, methods such as controlled atmosphere storage, vacuum cooling, or freezing can be better options. To prevent tomatoes from drying out and shrinking in the fridge, you can increase the humidity inside the fridge, either by using a humidifier or by placing a bowl of water inside.

If you store tomatoes at higher temperatures, they tend to become sweeter, but they also lose more weight, and their firmness decreases after about 9 days. On the other hand, if you keep them at lower temperatures, such as 13°C, their overall quality is better preserved. This includes factors like color, firmness, pH levels, sweetness, sourness, and weight loss.[44]

2.3 Conclusions

Tomato storage, especially in countries with challenging climatic conditions like Pakistan, requires a detailed and nuanced approach. While various studies have explored different facets of cold storage, there remains a need for a comprehensive, energy-efficient, and tomato-specific solution.

CHAPTER 3: DESIGN CALCULATION AND METHODOLOGY

In the previous chapter a detailed literature review regarding minimizing the post-harvest losses, enhancing food security, Energy outage. This chapter is about the methodology used for cooling load calculation, selecting refrigeration equipments and overall working of cold storage box. Designing a customized solar powered refrigeration system is a complex task and one can face many problems. Below is the overall procedure of load calculation, selection of refrigeration equipments and working of cold storage.

3.1 Tomatoes Thermal Properties

Food refrigeration presents significant challenges to engineers since food composition, structure, and physical and thermal qualities vary considerably. In addition, food properties vary with temperature and time of day. The fact that fruits and vegetables release carbon dioxide, water vapor, and other gases during storage and require oxygen presents an additional problem.[45]

Foods' water content has a significant impact on their thermal characteristics. In reality, food's specific and latent heats may be determined rather accurately only by looking at their water content. Siebel's formula can be used to express the specific temperatures of meals as

$$C_{p,\ fresh} = 3.35\ a + 0.84$$

$$C_{p,\ frozen} = 1.26\ a + 0.84$$

where $C_{p,\ fresh}$ and $C_{p,\ frozen}$ are the food's specific heats before and after freezing, respectively; “a” is the fraction of food's water content; so if the water content is 94%, "a" = 0.94. Finally, the food's solid (nonwater) portion's specific heat is represented by the constant 0.84 kJ/kg · C.

For example, the specific temperatures of both fresh and frozen tomatoes with a 94% water content are

$$C_{p,\ fresh} = 3.35\,(0.94) + 0.84 = 3.989\ \text{kJ/kg} \cdot {}^\circ\text{C}$$

$$C_{p,\ frozen} = 1.26\,(0.94) + 0.84 = 2.024\ \text{kJ/kg} \cdot {}^\circ\text{C}$$

The water content of a food product effects its latent heat during freezing or thawing, which is also known as the heat of fusion and is determined from

$$h_{latent} = 334\ a\ (kJ/kg)$$

$$h_{latent} = 334\ (0.94)$$

$$h_{latent} = 313.96$$

The Heat and Mass Transfer book by YUNUS A. ÇENGEL additionally provides information on the specific heat of vegetables (tomatoes) at temperatures below and above freezing as well as the latent heat. The table is provided below.

Table 3. 1: Specific heat and freezing point properties of common food[45]

Food	Water content,[a] %(mass)	Freezing Point[a] °C	Specific heat,[b] kJ/kg·K Above Freezing	Below Freezing	Latent Heat of Fusion,[c] kJ/kg
Vegetables					
Artichokes	84	−1.2	3.65	1.90	281
Asparagus	93	−0.6	3.96	2.01	311
Beans, snap	89	−0.7	3.82	1.96	297
Broccoli	90	−0.6	3.86	1.97	301
Cabbage	92	−0.9	3.92	2.00	307
Carrots	88	−1.4	3.79	1.95	294
Cauliflower	92	−0.8	3.92	2.00	307
Celery	94	−0.5	3.99	2.02	314
Corn, sweet	74	−0.6	3.32	1.77	247
Cucumbers	96	−0.5	4.06	2.05	321
Eggplant	93	−0.8	3.96	2.01	311
Horseradish	75	−1.8	3.35	1.78	251
Leeks	85	−0.7	3.69	1.91	284
Lettuce	95	−0.2	4.02	2.04	317
Mushrooms	91	−0.9	3.89	1.99	304
Okra	90	−1.8	3.86	1.97	301
Onions, green	89	−0.9	3.82	1.96	297
Onions, dry	88	−0.8	3.79	1.95	294
Parsley	85	−1.1	3.69	1.91	284
Peas, green	74	−0.6	3.32	1.77	247
Peppers, sweet	92	−0.7	3.92	2.00	307
Potatoes	78	−0.6	3.45	1.82	261
Pumpkins	91	−0.8	3.89	1.99	304
Spinach	93	−0.3	3.96	2.01	311
Tomatos, ripe	94	−0.5	3.99	2.02	314
Turnips	92	−1.1	3.92	2.00	307

3.2 Vegetables and fruits refrigeration

To maintain preharvest freshness and flavor as well as to increase storage and shelf life, fruits and vegetables are often chilled. Precooling is the process of cooling a product before it is transported to a market or storage facility. Both the cooling techniques and the cooling requirements of fruits and vegetables vary significantly. Products that should be refrigerated as soon as possible after harvesting include broccoli, ripe tomatoes, carrots, green vegetables, apricots, strawberries, peaches, and plums. Long-lasting fruits and vegetables including potatoes, pumpkins, green tomatoes, and apples don't require or benefit from cooling.

This exothermic reaction releases respiration heat, which increases the refrigeration load when fruits and vegetables are being cooled. Temperature has a significant impact on the rate of respiration. Additionally, the heat of respiration varied significantly amongst products. Most vegetables lose heat during their respiration process over time. The heat of respiration of some fruits and vegetables are given below from ASHRAE Handbook of Fundamentals, chap 30.

Table 3. 2: Respiration heat values of different fruits and vegetables

	Heat of respiration, mW/kg	
Product	5°C	20°C
Apples	13–36	44–167
Strawberries	48–98	303–581
Broccoli	102–475	825–1011
Cabbage	22–87	121–437
Carrots	20–58	64–117
Cherries	28–42	83–95
Lettuce	39–87	169–298
Watermelon	*	51–74
Mushrooms	211	782–939
Onions	10–20	50
Peaches	19–27	176–304
Plums	12–27	53–77
Potatoes	11–35	13–92
Tomatoes	*	71–120

Below is the equation used for refrigeration load due to respiration.

$$\dot{Q}_{respiration} = \sum m_i q_{respiration} \text{ (W)}$$

which is the total mass times the heat of respiration for all food items kept in the refrigerated area. Since fresh produce has the highest respiration rates, it is the most perishable, thus refrigeration is the most efficient means of reducing respiration and degradation.

$$\dot{Q}_{respiration} = (1000\text{kg})\ (120\text{mW/kg})$$

$$\dot{Q}_{respiration} = 120000\ (\text{mW})$$

$$\dot{Q}_{respiration} = 120\ (\text{W})$$

3.3 Storage requirement of Tomatoes

For most of the fruit and vegetable varieties, the different storage temperatures and relative are suggested [46]. For tomatoes it is recommended to store mature green tomatoes above 10°C to avoid their deterioration during ripening. Temperatures between 20 and 22°C and relative humidity (RH) between 90 and 95% are ideal for commercial ripening; however, ripening can be slowed without increasing degradation at 14 to 16°C. Applying ethylene gas, usually at a concentration of 1 part ethylene per 5000 parts of air daily for 2-4 days at 20–22°C, may accelerate the ripening process. Low temperatures, which raise the risk of deterioration during ripening, are harmful. Firm, ripe tomatoes store well for a week or less at 7–10°C and 85–90% relative humidity. Tomatoes with a surface color of 50–70% should not be stored for longer than that [47].

Table 3. 3: Temperature and RH range for different Cold room application[48]

	Scientific Name	Storage Temp, °C	Relative Humidity, %	Highest Freezing Temp, °C	Respiration Rate	Approximate Postharvest Life
Tomato						
Mature, green	Lycopersicon Esculentum	10 to 13	90 to 95	-0.5	Low	2 to 5 weeks
Firm, ripe	Lycopersicon Esculentum	8 to 10	85 to 90	-0.5	Low	1 to 3 weeks

3.4 Cooling load of cold storage room

To keep the cold storage at the proper low temperature, a refrigeration system needs to be sufficiently large to exclude any heat gain. As a result, the rate of heat gain of a cold storage is used to calculate the size of a refrigeration system for that specific box. The term "refrigerated load" refers to the total rate of heat gain of a refrigerated space through all mechanisms during highest demand conditions. It is made up of the following: [49]

(1) Transmission load, which is heat conducted into the refrigerated space through its walls, floor, and ceiling.

(2) Infiltration load, which is the result of warm ambient air entering the refrigerated space through cracks and open doors.

(3) Product load, it refers to the amount of heat extracted from food items during the cooling process to reach refrigerated temperature.

(4) Internal load, is heat produced by the people, lights and electric motors in the cooling space; and

(5) Refrigeration equipment load is the heat generated by the cooling equipment by performing different tasks such as reheating and defrosting.

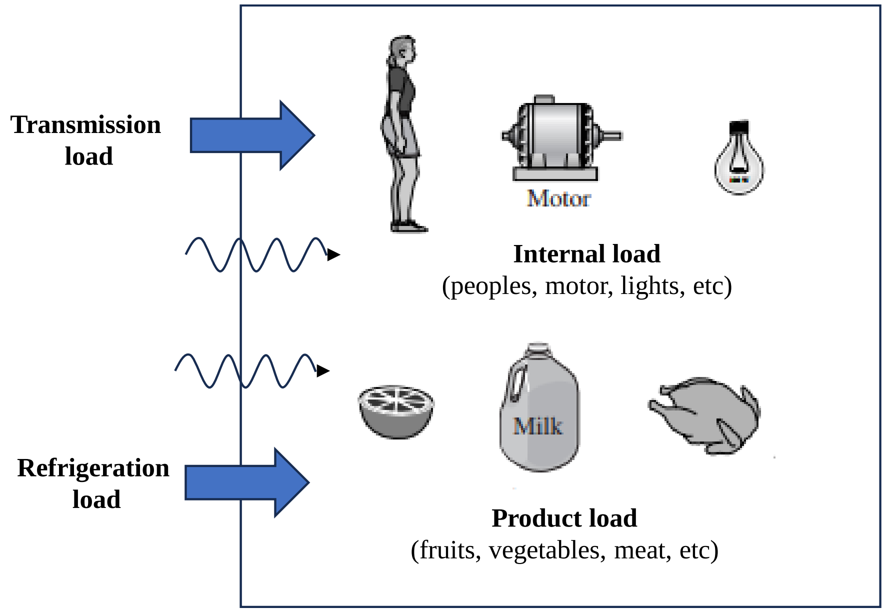

Figure 3. 1: Total Refrigeration load of a refrigerated space

3.5 Design Calculation:

3.5.1. Cooling System:

After in depth literature review Cold Storages both mechanically refrigerated and without refrigerated cold storages are used for maintaining cooling. As tight control of temperature and relative humidity inside is required so mechanical refrigerated system is used for cooling. The design conditions of the cold storage box are given in the table below.

Table 3. 4: Cold storage box design condition

Room conditions:	
Location	Pakistan
Temperature:	4.0 °C
Relative humidity:	90.0 %
Dimensions:	
External Length:	1.95 m
External Width:	1 m
External Height:	1.22 m
Walls, floor and roof area of Cold Storage	$11m^2$
Internal Volume of Cold Storage	$1.2m^3$
Goods:	
Type:	Vegetables (Tomatoes)
Product Quantity	500 kg
Inlet temperature:	35 °C
Air exchange (infiltration):	
Temperature:	45.0 °C
Relative humidity:	95 %
Door openings:	Rare
Air exchange rate:	1.25/h
Heat transfer:	
Panel thickness:	100.0 mm
Temperature of surroundings:	45.0 °C
Temperature below floor:	35.0 °C
Floor is insulated:	Yes
Others	
Product loading temperature	35°C
Latitude	33.6844° N
Longitude	73.0479° E

Elevation / Altitude	508 m
Insulation Material	Polyurethane
Insulation Thickness	100mm
Wind speed	3.8 m/s

A compartment of 12 inches width, 48 inches height and 40 inches length are made to place compressors, condenser fans and batteries. Internal dimensions of the cold storage box are shown in Figure 3.2.

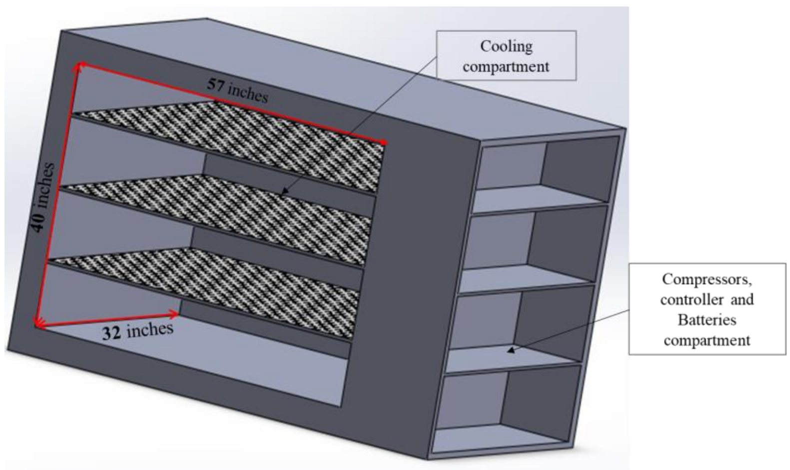

Figure 3. 2: Inside dimension of Cold Storage/Reefer container showing storage and compressors compartment.

The internal volume and area are calculated and provided in the Table below.

Table 3. 5: Internal Dimension of components

Components	Dimension
Volume of Box	$1.2m^3$
Area of Roof	$2m^2$
Area of Floor	$2m^2$
Area of Walls	$6.5m^2$
Total Area of Box	$10.5m^2$

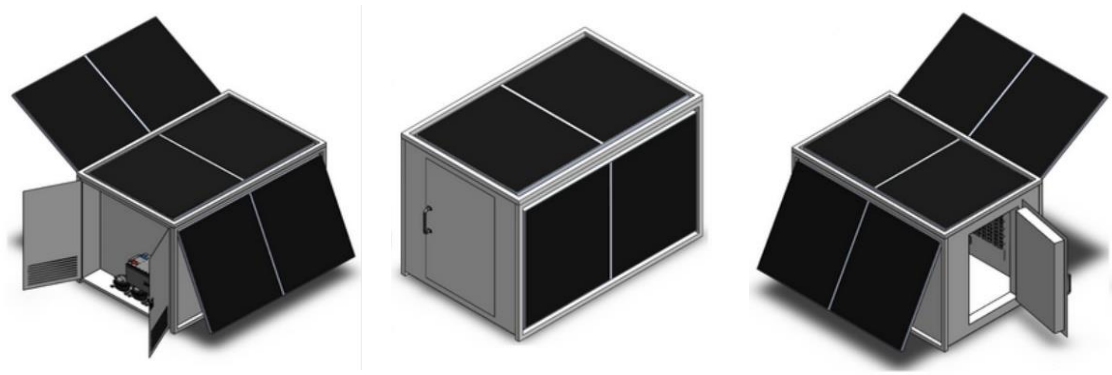

Figure 3. 3: 3D Model of Cold Storage/Reefer container showing solar panels arrangement

3.3. Insulation material selection:

It is important to use efficient insulating materials while constructing refrigerated rooms to reduce the amount of refrigerated space per given floor area. Polyurethane is a common insulation material used for cold storages due to its high R-value. As this cold storage is designed for multiple producers, considering change in temperature from 0°C to 10°C insulation of 100 mm was selected. Table 4 shows the minimum polyurethane (expanded) insulation thicknesses (k=0.029 W/m· C) that the ASHRAE Handbook recommends [35].

Table 3. 6: Minimum insulation thicknesses[14]

Storage Temperature (°C)	Expanded polyurethane insulation thicknesses (mm)	
	Northern U.S	Southern U.S
10 to 16	50	50
4 to 10	50	50
-4 to 4	50	75
-9 to -4	75	75
-18 to -9	75	100

Different produce can be placed inside a cold storage box but for calculation purpose of cooling load tomatoes (500kg) are considered to be placed inside cold storage with required minimum temperature of 4°C and relative humidity of 90%. Below is a summary (Table 4) of required temperature and relative humidity for storing tomatoes.

3.4 Cooling Load Calculations:

The refrigerated load, also known as the cooling load (shown in Figure 3.4), is the total rate of heat gain of a refrigerated area through all mechanisms at peak demand conditions. the load comprises of transmission load, infiltration load, product load, internal load and equipment load [15]:

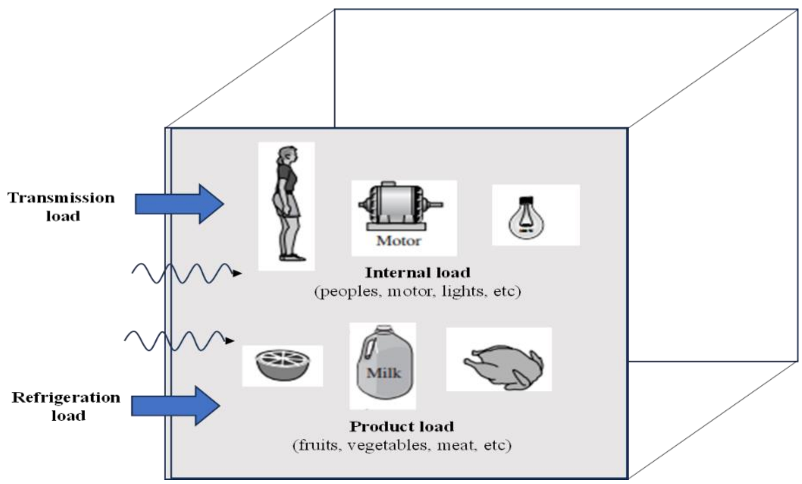

Figure 3. 4: Total Refrigeration load of a refrigerated space

The following assumptions are made for cold storage box.

- 70% of internal volume is utilized so that air can easily circulate inside cold storage.
- The size of rectangular tomato plastic crates is 1.5ft x 1ft x 0.84ft = 1.26ft^3.
- Approximately 20kg of tomatoes are placed inside the crate of volume 1.26ft^3.
- The total amount of tomatoes that we can store inside Cold Storage Box is 24 (24x 20kg = 480kg) 500kg of tomatoes are considered to be placed inside cold storage.

- The ambient temperature is supposed to be 45°C and the product is placed at 35°C because tomatoes are washed before placing which act as precooling.
- The Condensation temperature is set to be 10°C above the ambient temperature and the actual condensation temperature is 45 + 10 = 55°C.
- Refrigerant temperature is set to be –10°C lower than the evaporation temperature of 4°C. Therefore, the actual refrigerant temperature is set to be, 4 + (–10) = –6°C.
- Solar panels are installed on the top and two walls of cold storage and are supposed of zero resistance to heat transfer.

3.4.1 Transmission Load

The transmission load is the total heat transfer through cold room wall, roof and floor, mainly depends on the construction. Refer to Figure 3.5.

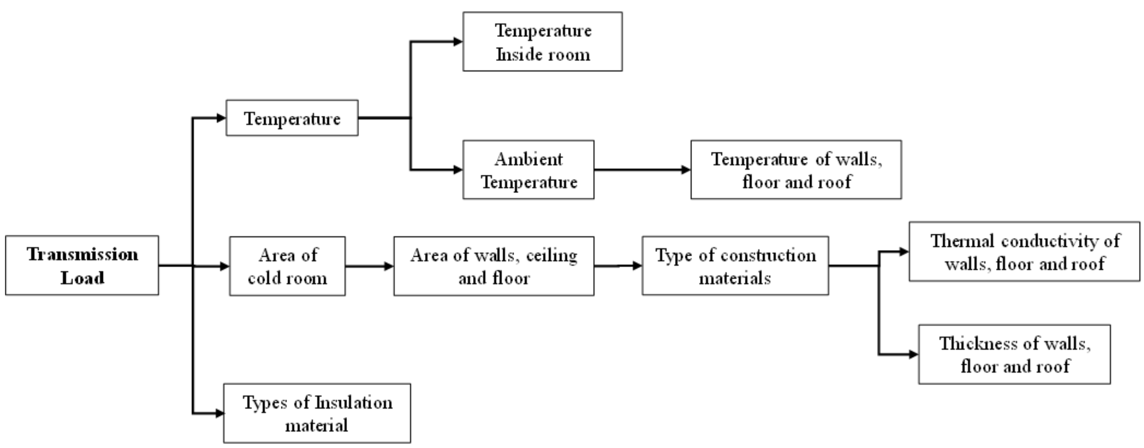

Figure 3. 5: Transmission Load Flow Chart

To determine the heat transfer rate through a particular wall, floor and roof Eq. (1) is used.

$$\mathbf{Q}_{\mathbf{Transmossion}} = U.A.\Delta T \qquad (1)$$

where

U = overall heat transfer coefficient

A = outside surface area of the box

ΔT = temperature difference between the inside air of refrigerated space and outside air.

Keeping in view that the layer's thickness to thermal conductivity ratio shows its unit thermal resistance, the thermal resistance diagram below (Figure 3.6) can be used to compute the overall heat transfer coefficient given by Eq. (2).

$$R_{total} = \frac{1}{h_i} + \sum \frac{L}{K} + \frac{1}{h_o}$$

$$U = \frac{1}{R_{total}} \qquad (2)$$

where

h_i = inside heat transfer coefficient of refrigerated space

h_o = outside heat transfer coefficient of refrigerated space

$\sum \frac{L}{K}$ = sum of the layers thickness and thermal-conductivity ratios

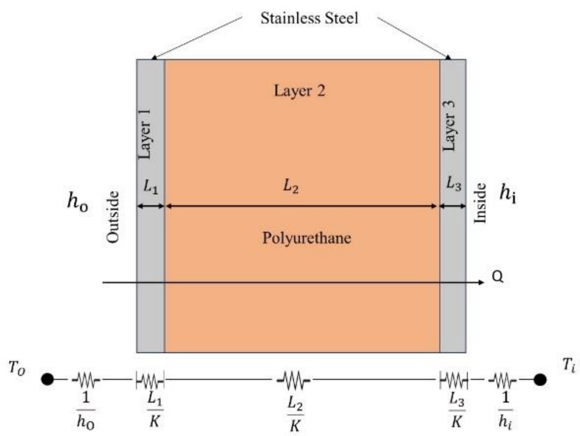

Figure 3. 6: Thermal resistance diagram of three-layer wall showing the effect of heat transfer coefficient for calculation of transmission losses.

Usually 10 W/m^2.°C is used for both h_o and h_i in still air. For low or moderate wind conditions outside, h_o can be set to 20 or 30 W/m^2.°C, accordingly. Table 6 displays alternate constant interior/exterior convection and combined surface coefficient for each surface type.

Table 3. 7: Comparison of Coefficients

Surface Type	Interior	
	Convection Surface Coefficient (h,conv,int) W/(m²·K)	Combined Surface Coefficient (h,comb,int) W/(m²·K)
Wall	2.2	1.8
Roof	1.8	1.7
Raised Floor	2.2	3.7
	Exterior	
	Convection Surface Coefficient (h,conv,ext) W/(m²·K)	Combined Surface Coefficient (h,comb,ext) W/(m²·K)
Wall	11.9	21.6
Roof	14.4	21.8
Raised Floor	0.8	5.2

3.4.1.1 Heat Transfer through Walls:

A door of $0.56m^2$ area is considered for the cold storage box. Since the materials and their specification for door and wall are same, heat calculation will be same as wall heat calculation. Here the door is considered as wall material and calculation for heat transfer is given by following equations.

$$R_{total,Wall} = R_{conv,1} + R_{Layer,1} + R_{Layer,2} + R_{Layer,3} + R_{conv,2} \quad (3)$$

$$R_{total,Wall} = \frac{1}{h_i} + \frac{L_1}{K_{SS,1}} + \frac{L_2}{K_{PU2}} + \frac{L_3}{K_{SS,3}} + \frac{1}{h_o} \quad (4)$$

The interior Combined Surface Coefficient h_i and the exterior Combined Surface Coefficient h_o values are taken from the above table.

Put values in equation (4)

$$R_{total,Wall} = \frac{1}{1.8\frac{W}{m^2.k}} + \frac{0.002m}{15.6\frac{W}{m.k}} + \frac{0.1m}{0.029\frac{W}{m.k}} + \frac{0.002m}{15.6\frac{W}{m.k}} + \frac{1}{21.6\frac{W}{m^2.k}}$$

$$R_{total,Wall} = 4.05\ \frac{m^2.k}{W}$$

Put values in eq (2)

$$\mathbf{U} = 1/R = 1/4.05 = 0.246\ \frac{W}{m^2.k} = \mathbf{0.246}\ \frac{\boldsymbol{W}}{\boldsymbol{m^2}.°\mathbf{C}}$$

To compensate for the solar heating effect of the east and west walls, for example, one can add 4°C to the surrounding air temperature, 3°C to the effect of the south wall, and 9°C to the ambient temperature in rooms with medium-colored surfaces, like unpainted wood, brick, and dark cement [14]. As a reefer container the direction of the wall will change and to make the calculation simple, the temperature of walls exposed to direct sunlight are considered to be 50°C when ambient temperature is 45°C.

Put values in eq (1)

$$Q_{\text{Transmossion,Wall}} = (0.246\frac{W}{m^2.°C})\ (6.5m^2)\ (50°C - 4°C)$$

$$\mathbf{Q_{Transmossion,Wall} = 73.6W \approx 74W}$$

3.4.1.2 Heat Transfer through Roof:

$$R_{total,Roof} = \frac{1}{1.7\frac{W}{m^2.k}} + \frac{0.002\text{m}}{15.6\frac{W}{m.k}} + \frac{0.1\text{m}}{0.029\frac{W}{m.k}} + \frac{0.002\text{m}}{15.6\frac{W}{m.k}} + \frac{1}{21.8\frac{W}{m^2.k}}$$

$$R_{total,Roof} = 4.082\ \frac{m^2.k}{W}$$

$$\mathbf{U} = 1/R = 1/4.082\ \mathbf{= 0.2449}\ \frac{\boldsymbol{W}}{\boldsymbol{m^2.k}}$$

As the roof of the cold storage box is exposed to direct sun light so the temperature of the roof surface is supposed to be at 50°C.

$$Q_{\text{Transmossion,Roof}} = (0.2449\frac{W}{m^2.°C})\ (2m^2)\ (50°C - 4°C)$$

$$\mathbf{Q_{Transmossion,Roof} = 22.5W}$$

3.4.1.3 Heat Transfer through Floor:

$$R_{total,Floor} = \frac{1}{3.7\frac{W}{m^2.k}} + \frac{0.002\text{m}}{15.6\frac{W}{m.k}} + \frac{0.1\text{m}}{0.029\frac{W}{m.k}} + \frac{0.002\text{m}}{15.6\frac{W}{m.k}} + \frac{1}{5.2\frac{W}{m^2.k}}$$

$$R_{total,Floor} = 3.911\ \frac{m^2.k}{W}$$

$$\mathbf{U} = 1/R = 1/4.082\ \mathbf{= 0.2556}\ \frac{\boldsymbol{W}}{\boldsymbol{m^2.k}}$$

As the floor of the cold storage box is not exposed to direct sun light so the temperature of the roof surface is supposed to be at 35°C.

$$Q_{\text{Transmossion,Floor}} = (0.2556 \frac{W}{m^2.°C}) (2m^2) (35°C - 4°C)$$

$$\mathbf{Q_{\text{Transmossion,Floor}} = 16W}$$

$$Q_{\text{Transmossion,Total}} = 74W + 22.5W + 16W$$

$$\mathbf{Q_{\text{Transmossion,Total}} = 112.5W}$$

3.4.2 Infiltration Load

This is the result of cracks, holes and open doors allowing warm ambient air to enter the refrigerated chamber as depicted by block diagram in Figure 3.7. The rate by which infiltration heat gain occurs can be determined from ASHRAE, Handbook.

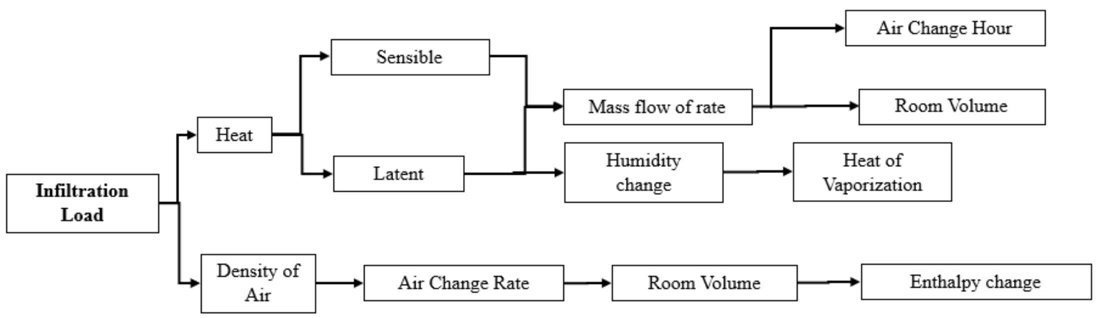

Figure 3. 7: Infiltration load

The expected number of air changes per hour is used via Eq. (5) to compute the mass flow rate of air entering the room [36].

$$\dot{m}_{air} = \frac{V_{room}}{V_{air}} \text{ x ACH} \qquad (5)$$

where

V_{room} = volume of the room

V_{air} = specific volume of the dry air in the room

ACH = Air change per hour

The ACH for this case ($2.36m^3$) is taken 30 per 24hr because the cold storage size is small in comparison. The specific volume of the dry air in the room can be found by Ideal gas law under certain conditions.

$$\mathbf{PV = mRT}$$

Where:

P = pressure of the dry air

V = specific volume,

m = mass of the dry air,

R = specific gas constant for dry air, and

T = temperature of the dry air in Kelvin.

By rearranging the equation for specific volume (v), we get:

$$\mathbf{V}= \frac{\boldsymbol{mRT}}{\boldsymbol{P}}$$

By putting values

$$\text{V}= \frac{(1.109kg)(287j/kg.k)(318.15k)}{101325pa}$$

$$\text{V}= \frac{(1.109)(287)(318.15)}{101325}\frac{\text{m}^3}{\text{kg}}$$

$$\mathbf{V= 0.994}\,\frac{\mathbf{m^3}}{\mathbf{kg}}$$

Equation (4) becomes.

$$\dot{\text{m}}_{\text{air}} = \frac{1.2\text{m}^3}{0.994\frac{\text{m}^3}{\text{kg}}}\text{x } 1.25/\text{hr}$$

$$\dot{\text{m}}_{\textbf{air}}\mathbf{= 0.000419\ kg/s}$$

When these values are known, the latent and sensible infiltration loads of the cold storage box can be calculated from the equations below.

$$\mathbf{Q_{infiltration,sensible}} = \dot{\text{m}}_{\mathbf{air}}(\mathbf{h_{ambient}} - \mathbf{h_{room}})$$

where

$\dot{\text{m}}_{\text{air}}$= mass flow rate of air

h= enthalpy of air

The value of enthalpy is taken from property table of Air at ambient and room temperature.

$$\text{Q}_{\text{infiltration,sensible}} = 0.000419\ \text{kg/s}\ (168.89 - 12.673)\ \text{kJ/kg}$$

$$\mathbf{Q_{infiltration,sensible} = 0.0654\ KW \approx 65W}$$

The latent heat can be calculated from the formula below.

$$\mathbf{Q_{infiltration,latent}} = (\boldsymbol{\omega}_{\mathbf{ambient}} - \boldsymbol{\omega}_{\mathbf{room}})\ \dot{\text{m}}_{\mathbf{air}}.\ \mathbf{h_{fg}}$$

where

ω = humidity ratio of air (the mass of water vapor in 1 kg of dry air)

h_{fg}= heat of vaporization of water.

If the values of temperature and relative humidity of the air are known, psychrometric chart can be used to calculate the values of the humidity ratio (ω) [37]. In present case the latent heat load to be zero as the aim is cooling tomatoes and not freezing.

The sum of the sensible and latent components is then the total infiltration load.

$$Q_{infiltration,total} = Q_{infiltration,sensible} + Q_{infiltration,latent}$$

$$Q_{infiltration,total} = 65W + 0W$$

$$\mathbf{Q_{infiltration,total} = 65\ W}$$

3.4.3 Product Load

This is the amount of heat taken from food items to bring them down to a required storing temperature. Product load distribution is given in Figure 3.8. About 55-75% of the cooling load is made up of product loads [37]. When the ambient temperature is 45°C, tomatoes after washing are precooled and are considered to be at 35°C. 500 kg of tomatoes with a specific heat capacity of 1.88 kJ/kg.°C are kept in storage at 35°C and are required to be cooled to 4°C.

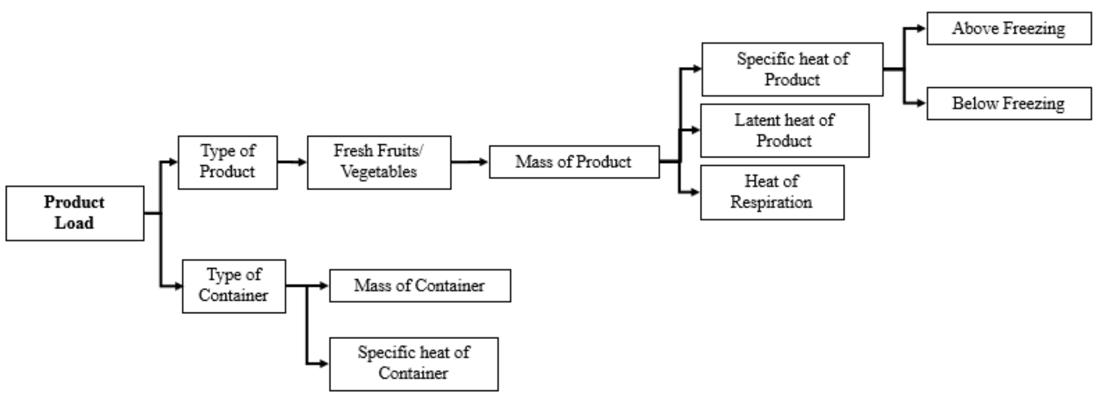

Figure 3. 8: Product Load

We can use the below formulas.[36]

$$\mathbf{Q_{cooling,Fresh} = mc_{p,fresh}\,(T_1 - T_{store})}$$

where

m = mass in kg of product exchange per day

$C_{p,fresh}$ = specific heat of the food before freezing

T_{store} = storage temperature of the food

T_1 = initial temperature of the food (before refrigeration)

It is assumed that the product will be stored in cold storage for a week and then it will be refilled.

$$Q_{cooling,Fresh} = (500kg)(1.88\frac{kJ}{kg.°C})(35°C - 4°C)$$

$$Q_{cooling,Fresh} = 29140 \text{ kJ}$$

To convert from kJ to kWh

$$Q_{cooling,Fresh} = \frac{29140 \text{ kJ}}{3600\ (24)}$$

$$\mathbf{Q_{cooling,Fresh} = 0.337kW = 337W}$$

Food products are refrigerated in the box, and cooling box is also included in the product load. The following equation can be used to calculate how much heat has to be removed from the box when it cools from T1 to T2.[36]

$$\mathbf{Q_{box} = mc_{p,container}\,(T_{1-}\ T_2)}$$

where

m = is the mass of the container

$C_{p,container}$ = is the specific heat of the container, which is 1.9 kJ/kg. °C for polyurethane.

T_1= initial temperature of the food (before refrigeration)

T_2= final temperature of the food (after refrigeration)

By putting required values

$$Q_{box} = (200kg)\ (1.9kJ/\ kg.°C)(35 - 4)\ °C$$

$$Q_{box} = 11780 \text{ kJ}$$

$$Q_{box} = \frac{11780 \text{ kJ}}{3600(24)}$$

$$\mathbf{Q_{box} = 0.136\ kW = 136\ W}$$

3.4.4 Tomato respiration rate (Product load).

Vegetables emits heat which is called respiration heat. This constitutes the reason for cooling tomatoes to slow the deterioration rate and preserve tomatoes for longer times [37]. In this case the cold box has capacity of 550kg of tomatoes when 70% internal space is utilized. Below is the equation used for refrigeration load due to respiration.

$$\dot{Q}\ \textbf{respiration} = \sum \mathbf{m_i q_{respiration}}$$

$$\dot{Q}\ \text{respiration} = (500\text{kg})\ (90\text{mW/kg})$$

$$\dot{Q}\ \textbf{respiration} = \mathbf{45W}$$

$$\text{Total product load} = Q_{\text{cooling,Fresh}} + Q_{\text{box}} + Q_{\text{respiration}}$$

Total product load = 518W

3.4.5 Internal Load

The total quantity of heat generated in the refrigerated area by the electric motors, lights, people, and other heat-dissipating machinery is called internal load as shown in Figure 3.9. The number of people within cold storage determines the rate at which heat dissipates.

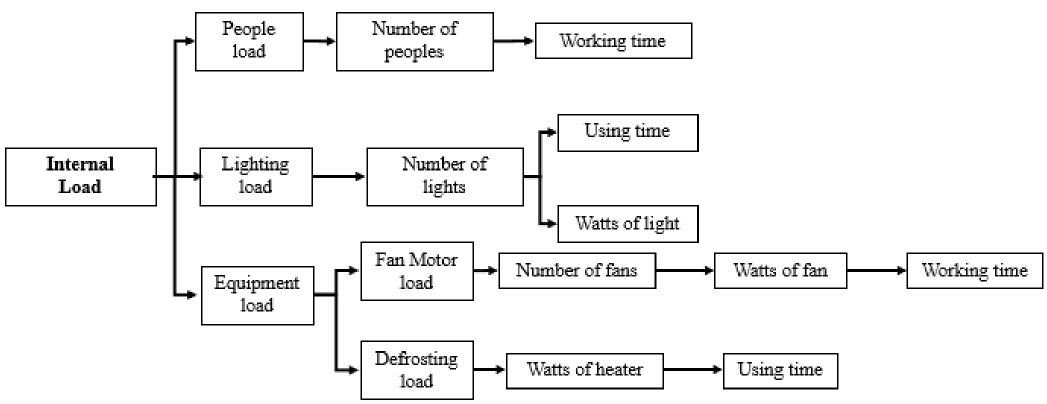

Figure 3. 9: Internal load

<u>3.4.5.1 People Load:</u>

The heat that a typical human would release in a refrigerator kept at T degrees Celsius is expressed as

$$Q\_people = n \times t \times P\_h \quad \text{(W/person)}$$

Where

n = Number of persons

t = working time in hours

P_h= Heat release per person (KW/person)

As this is a small size cold storage and not a walk-in storage so the value for people load are considered zero.

3.4.5.2 Lights:

Heat given up by the source of light is lighting load. It can be calculated by the rate of heat dissipation from lights by simply adding to the fluorescent tube and light bulb wattages. For example, this work is using 2 lights of 7 watts each and they are supposed to be used for 4 hr.

$$Q_{lights} = \frac{A \times P_v x\ t}{1000}$$

Where

A = Floor Area of Warehouse (m^2)

P_v= Lighting load (W/m^2)

t = lights on time (h/d)

Here 2 lights of 7 watts are supposed to be powered on for 4 hr.

$$Q_{lights} = \frac{1.4 \times 7\ x\ 4}{1000}$$

$$Q_{light} = 0.04W$$

3.4.5.3 Equipment Load:

In cold storage electric motor load is due to evaporator fan and no other equipment is considered inside cold storage. The fan load is calculated below.

3.4.5.4 Evaporator Fan Load:

The heat load of evaporator blowers and fans works on electrical power that contains a motor. Fans are used for circulating the air inside the cold storage. So, the watts of fans should be considered.

$$Q_{fan} = \mathbf{n\ x}\ \ P_{fan}\ \mathbf{x\ t}$$

where

n = number of fans (kWh/d)

P_v= Fan motor power input (kW)

t = Fan running time (h/d)

This research is using evaporators with natural convection, so no fan is used with evaporator.

$$Q_{fan} = \mathbf{0W}$$

<u>3.4.5.5 Evaporator Fan Load:</u>

Defrosting is the method of removing ice from the evaporator usually a heater is installed near evaporator to melt the ice on evaporator. Defrosting maintains the operation efficiency. In this case as the atmosphere is not going in negative temperature and freezing so defrosting load is not considered.

Total Internal Load = People load + Lights load + Electric Motor + Fan Load + Defrosting Load

Internal Load = 0W + 0.04W + 0W + 0W

Internal Load = 0.04 W

3.4.6 Total Cooling Load:

Total Cooling Load = Transmission load + Infiltration load + Product load + Internal Load

Total Cooling Load = 112.5 W+ 65W + 518W + 0.04W

Total Cooling Load = 695.54Watts

The safety factor of 10% to 20% is typically applied when calculating the overall refrigeration load.

Total Cooling Load = 695.54 W + Safety Factor of 10%

Total Cooling Load =765W

3.4.7 Cooling Capacity:

The Cooling capacity of a cold storage depends on the process, not on the volume. Assuming the cold storage operate 14 hours in a day

$$\text{Cooling capacity} = \frac{\text{Refrigeration Load}}{\text{Running Hours}}$$

$$\text{Refrigeration/ Cooling capacity} = \frac{765W}{14h} = \mathbf{54.6W}$$

After total cooling load calculation, next step is the selection of appropriate equipment. The process flow for the selection of the equipment is given below.

3.5 REFRIGERATION EQUIPMENT SELECTION

3.5.1 Compressor Selection

To meet the cooling requirements, a DC compressor of ($\frac{750}{746}$W) 1.005HP or a compressor of 0.21Ton is required. Coolselector software suggests a compressor and condensing unit of AC source which fulfill the requirement. The objective is to have a DC compressor, so multiple compressors of BD80F model are employed, where hermetic reciprocating compressor for R134a is used for refrigeration. The BD80F compressor is of 1/4 (0.25) HP. The requirement for cold storage box is $\frac{1.005}{0.25}$ = 4.02 ≈ 4 so 4 compressors of 0.25 HP are needed to meet requirements.

3.5.1.1 COP Calculation:

Using Psychrometric chart for the refrigerant (R134a), following values and parameters were selected for the operating pressure range of 25 psi to 300 psi [38]. Assuming these value of temperatures and refrigerant leaves the evaporator in wet saturated form and leaves the condenser at dry form, the refrigeration cycle is drawn on p–h chart given at Figure 12.

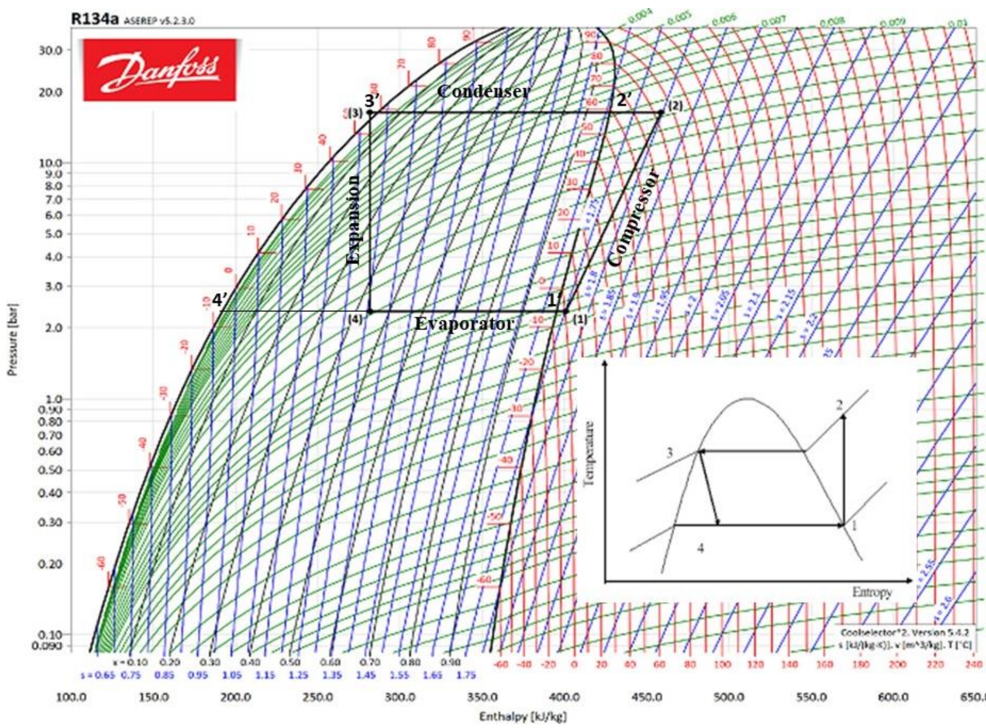

Figure 3. 10: Pressure-Enthalpy (Ph) and Pressure-Entropy (PS) diagram

Knowing the minimum and maximum pressure, the temperature, enthalpy and entropy of gas in both vapor and liquid form can be assessed. The property table of R134a for saturated vapor, superheated vapor is used to find unknown values. These values are provided in Table 9 [39].

Table 3. 8: Properties of R134a

State Points	**State Point 1**	**State Point 2**	**State Point 3**	**State Point 4**
Temperature (°C)	T_1= -15.6	T_2= 67.49	T_3= 66.28	T_4= -15.6
Pressure (Kpa)	P_1= 170	P_2= 2060	P_3= 2060	P_4= 170
Enthalpy (Kj/kg)	h_1= 238.8	h_2= 278	h_3= 153.94	h_4= 153.94

Entropy (Kj/kg.k)	S_1= 0.9281	S_2= 0.8934	S_3= 0.5311	S_4= 0.6
Comments	• Low Pressure and Temperature • Saturated Vapor	• High Pressure and Temperature • Super -heated Vapor	• High Pressure and medium Temperature • Saturated Liquid	• Low Pressure and Temperature • Liquid Vapor mixture

S_1= 0.9281 KJ/kg.K, S_2= 0.8934 KJ/kg.K, S_3= 0.5178 KJ/kg.K, S_4= 0.1294 KJ/kg.K

h_1= 238.8 kcal/kg, h_2= 277.94 kcal/kg, h_3= 31.615 kcal/kg, h_4= 31.615 kcal/kg

The refrigerant is superheated by 5°C; therefore temperature T_1'= -15.6°C +5°C = -10.6°C. As the entropy at point 1 is equal to entropy at point 2, so following equations we can equate these.

S_1'= S1 + Cpln(T1'/T1) ------------- equation (1)

S_2'=S2 + Cpln(T2'/T2) ------------- equation (2)

Where Cp for R134a= 0.854kJ/kg·K

Equation (1) = Equation (2)

T_2=361.49K = **88.49°C**

$$\textbf{COP}= \frac{\textit{Refrigerating effect}}{\textit{Work done}} = \frac{h_1 - h_4}{h_2 - h_1}$$

T_3 is subcooled by 3°**C**, T_3'= 63.28336.28K= **63.28°C**

h_3'=h3 – Cp (T_3 - T_3') = 153.94kJ/kg - 0.854kJ/kg·K (66.28 - 63.28) °**C** =151.37kj/kg = h_4'

h_1'=h1 – Cp (T_1'- T_1) = 238.8kJ/kg - 0.854kJ/kg·K (-10 -(-15)) °**C** =234.5kj/kg

h_2'=h2 – Cp (T_2'- T_2) = 278kJ/kg - 0.854kJ/kg·K (88.49 – 67.49) °**C** =260kj/kg

$$COP_{Theoretical} = \frac{Refrigerating\ effect}{Work\ done} = \frac{h_1' - h_4'}{h_2' - h_1'} = \frac{234.5 - 151.37}{260 - 234.5} = \mathbf{3.26}$$

3.5.2. Condenser Design:

Condensers of various horsepower ratings i.e ¼ HP are available in the market. The design of Condenser depends on the amount of heat that a condenser needs to be removed, thus, to remove the required heat a condenser of diameter 3mm and a length of 60 feet are used with each compressor.

3.5.3. Capillary Tube:

A capillary of size 0.031 and length 9.5 feet are used, one for each compressor.

3.5.4. Evaporator Design:

As 4 compressors are used therefore, 4 evaporators are required, one for each compressor. Capacity of evaporator will be equal to the amount of refrigerating effect = 83kj/kg.3 An evaporator coil of soot 2.5 and length 30 feet is used for each refrigeration cycle.

3.6 METHODOLOGY

The objective is to design a cold storage which can also be used as a reefer container. The box is made of a moderate size so that it can be used both as cold storage and reefer container considering economical value and cooling possibility. The storage life depends on the product as calculation is made considering tomatoes where shelf life of ripe tomatoes is 3 to 7 days. The total internal volume of cold storage box is 1.2m^3. Solar panels are installed on the walls and top of cold storage box. Solar panels are used to convert solar energy to electrical energy. Maximum Power Point Tracking (MPPT) are installed which will run the compressor directly from solar panels during peak sun hours and will store the extra power generated by solar panels in the battery. The batteries will provide backup for off-peak hours. A microcontroller is installed which controls the system temperature by controlling the motor drive of DC compressors and relative humidity by turning on and off of humidifier. It also provides real time values of power generated by solar panels, the power utilized by compressors, light intensity and the power that are stored in batteries. Two DHT (Humidity and temperature) sensors are installed, one inside a cold storage box to control the temperature and relative humidity of cold storage box and the other at ambient atmosphere to detect the ambient temperature and relative humidity. The location of the reefer container can also be traced. A buzzer is installed for safety which will ring if any sudden change in the system is detected. A mobile or laptop is connected with microcontroller through Wi-Fi for data analysis and real time monitoring. Complete methodology is given in Figure 3.11. Similarly, PCB schematic of cold storage is displayed in Figure 3.12.

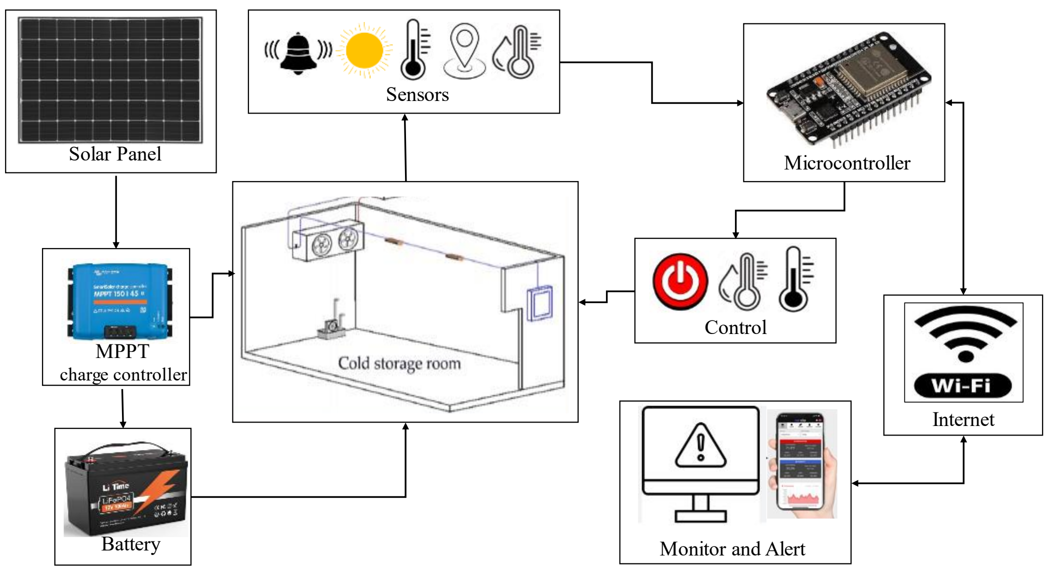

Figure 3. 11: Block Diagram

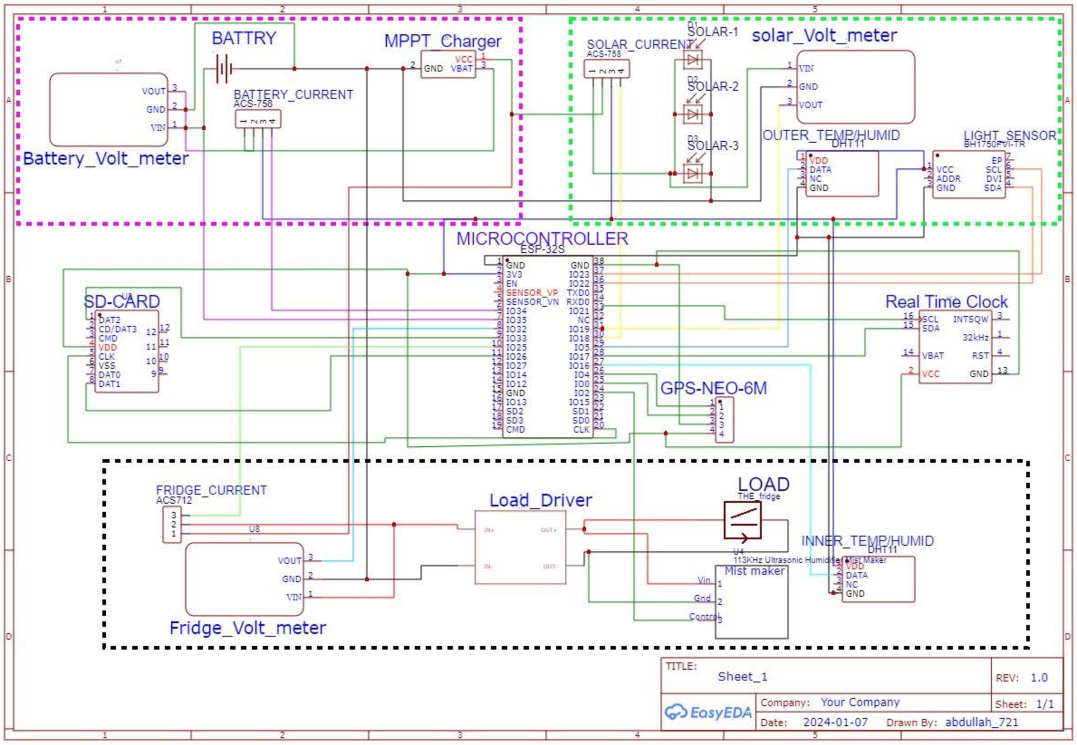

Figure 3. 12: PCB Schematic of Cold Storage

3.6.1 HARDWARE:

The system is designed for measuring and controlling temperature and relative humidity. The list of hardware components that are used in this design are given in Table 1 and displayed in Figure 3.

Table 3. 9: List of Hardware components

Components	Name of module	Quantity
Microcontroller	ESP32	1
High current sensor	ACS758	2
Current sensor	ACS712	1

Voltage sensor	Voltage divider	3
Temperature & Humidity sensor	DHT-11	2
Light Intensity Sensor	BH1750	1
Voltage Regulator	LM2596s	1
Real Time Clock Module	RTC-DS3231	1
GPS module	NEO-6m GPS	1
Memory card reader / writer	Micro SD TF card Module	1
Ultrasonic Humidifier	Halloween mini fogger	2

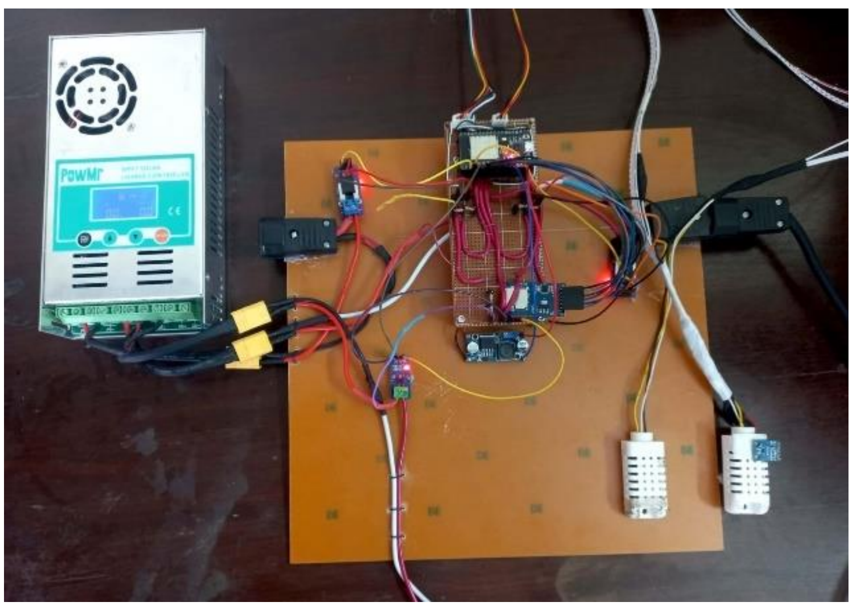

Figure 3. 13: Hardware assembly diagram

3.6.2 SOFTWARE:

Software for cold storage will allow users to remotely monitor and control the current and past data. The program for this design is written in Flutter with Dart language. As this cold storage can be used for multiple producers so user needs to specify the use of the cold storage box by selecting specific producers, required humidity, inside and ambient temperature. Users can get real time values of inside and outside temperature and relative humidity values of cold storage, current and voltage values of solar panels and batteries. As the sunlight intensity changes with time and weather condition so user can also check the intensity of light. An alarm can be set to ring when there is a sudden unusual change observed in temperature and a notification can be received on mobile. The location of cold storage can also be monitored if is used as reefer container.

CHAPTER 4: RESULT AND DISCUSSION:

4.1 Comparison of manual and software Cooling Load Calculations:

Table 4.1 below provides a compression between manual calculated cooling load and software calculated cooling load. The difference between the values is due to the selection of products to be placed inside cold storage. In manual calculation a single vegetables tomatoes are selected so to have single latent and specific heat values. Calculations are done considering all vegetables instead of single tomatoes. A significant load difference is observed in tomato cooling load because in software we have selected that the daily tomatoes change is zero means that once we load cold storage then we will open in after a week or more when needed.

Table 4. 1: Cold box load calculations

Type of load	Software Calculation	Manual Calculations
Transmission	128W	112.5W
Infiltration	140W	65W
Ice on evaporator	15W	0W
Tomato, cooling	359W	337W
Container Load	0W	136W
Tomato, respiration	25W	45W
Light	0W	0.04W
People	0W	0W
Fans	0W	0W
Defrost	0W	0W
Other	0W	0W
Total cooling load	667W	695W
Cooling load with 10% safety	**734W**	**765W**

4.2 Total cooling load:

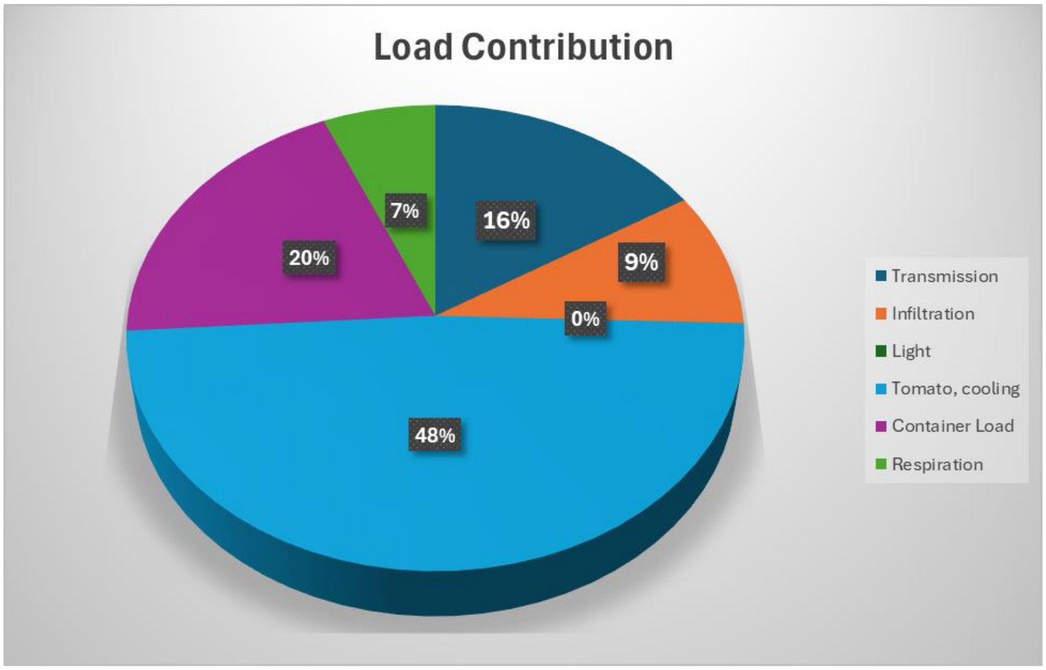

Figure 4. 1: Contribution of different loads in total cooling load calculation.

4.3 Temperature Distribution along the wall:

All walls of the container are supposed to be in the same ambient temperature. So single wall is analyzed to get the inside wall temperature of the box when there is no cooling source and to find the temperature distribution along the wall. There is convective and radiative heat transfer from outside high temperature to outside wall surface as the effict of radiative heat transfer is minor so it is neglected. The heat is transfer throught conduction along the walls. The ansys simulation (shown in Figure 4.2) shows that when the ambient temperature is 45°C and there is convective and conduction heat transfer. The inside wall temperature is 9.5377°C.

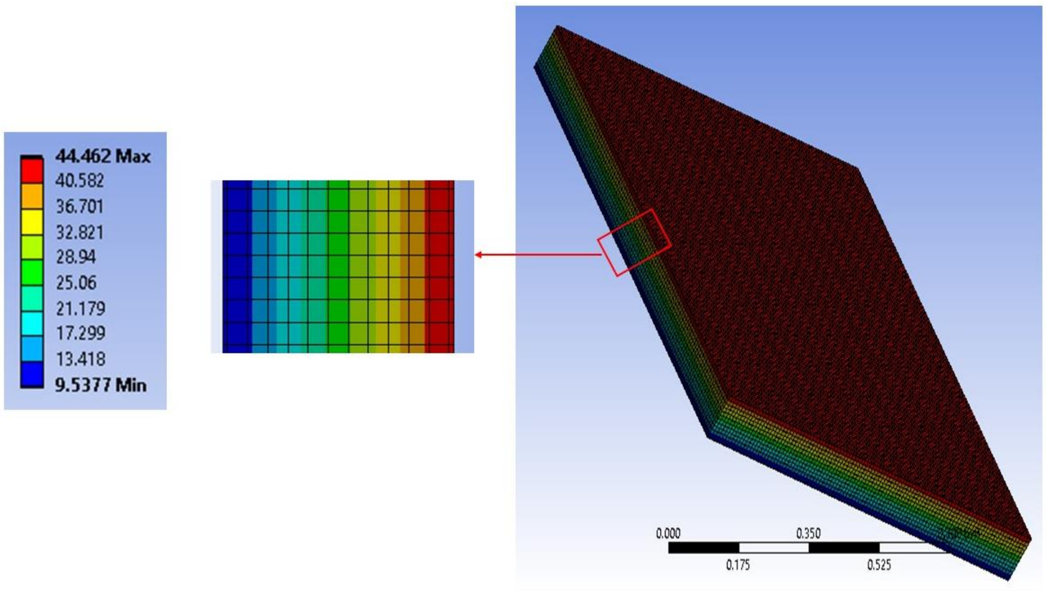

Figure 4. 2: Inside and Outside temperature distribution along the wall

4.4 Temperature distribution inside cold storage

The heat transfer on the inside surface is 9.5377°C without any cooling system inside. Now in order to drop the temperature to 4°C a refrigeration cycle is installed. The temperature of the evaporator is kept at -6°C and respiration heat of tomatoes is considered 50W. Figure 4.3 show the temperature distribution inside cold storage.

The graph given in Figure 4.4 shows that when the temperature of evaporator is -6°C, respiration heat of tomatoes is 50W and the inside wall temperature is 9.5377°C. It will take approximately 800 seconds to lower the inside air temperature to 4°C.

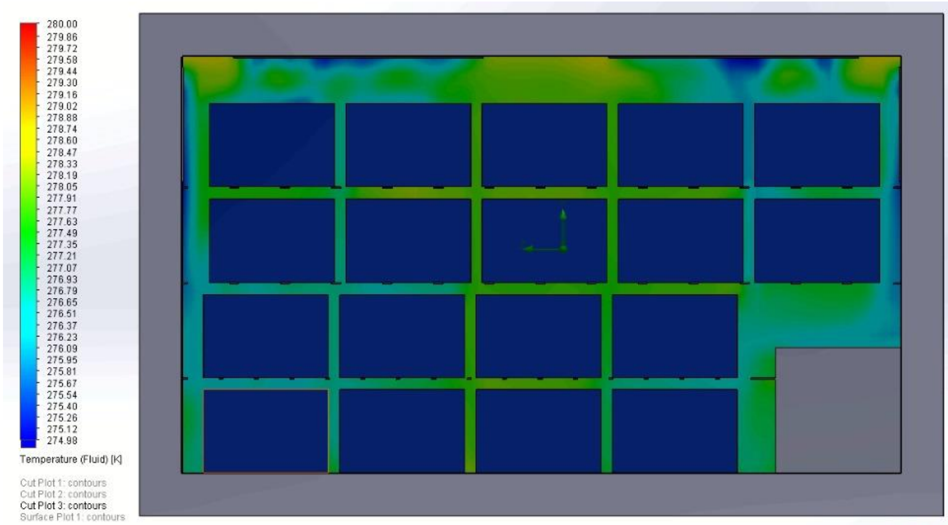

Figure 4. 3: Temperature distribution inside cold storage

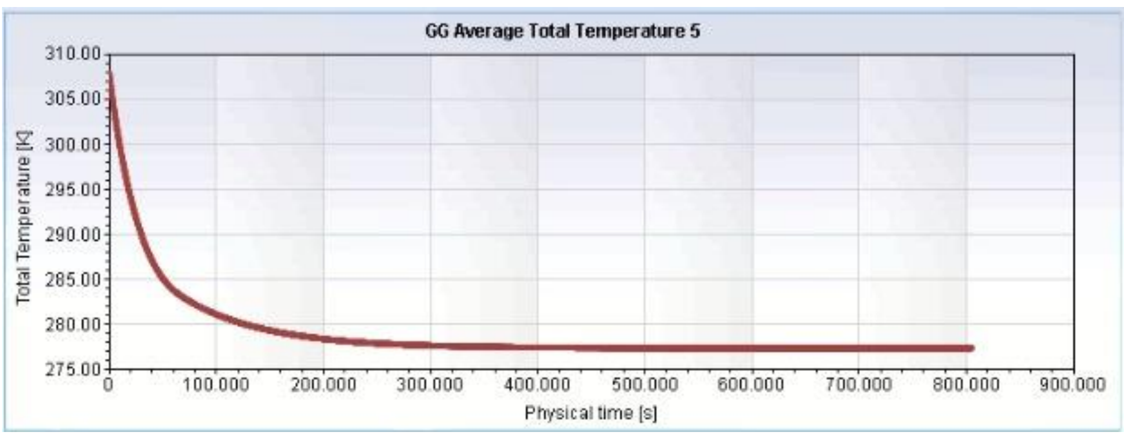

Figure 4. 4: Time versus Temperature graph

The simulation result in figure 4.5 shows that cold storage takes approximately 12000 seconds (three and half hours) to cold the tomatoes of 500kg from 35°C to 4°C.

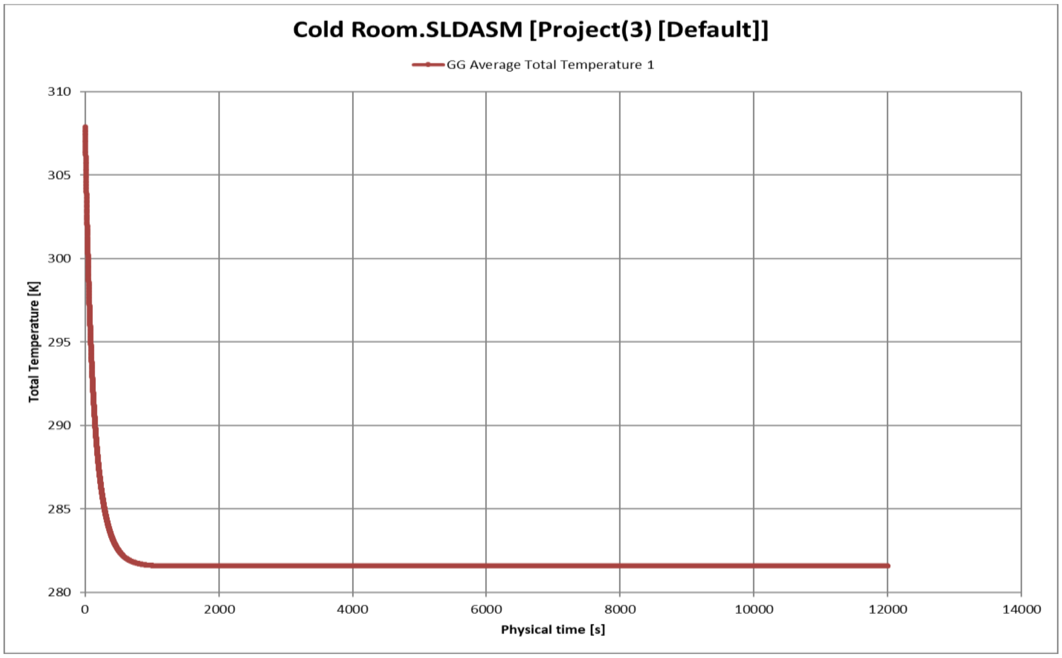

Figure 4. 5: Time versus Temperature graph

As the air passes through the evaporator coil it cools and leads to condensation where water vapors in the air become liquid. Thus, the water fraction near the evaporator is low as shown in Figure 4.5. Ultrasonic Humidifier are installed to maintain the relative humidity inside the cold storage.

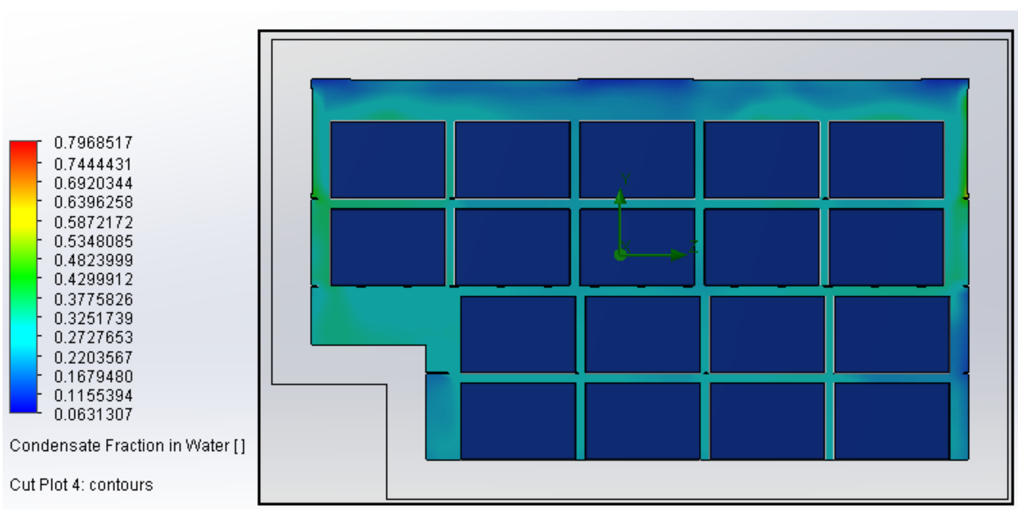

Figure 4. 6: Water fraction distribution inside cold storage

4.5 System Testing and Validation:

The software and hardware for IoT based control of temperature and relative humidity in a cold storage box of cooling load 765watts and 1200 liters is tested on a DC Chest Freezer of 72watts and 110 liters which is approximately 10 times smaller than the specification of the Cold Storage box. The temperature and relative humidity sensors are installed inside and outside of 110 liters freezer. 40 liters of water having temperature of 35°C is placed inside DC chest freezer a temperature sensor probe is placed inside the water to get the water temperature. The temperature values of inside water, inside and outside freezer are sensed after every 5 minutes. To control relative humidity, an ultrasonic humidifier is installed and are controlled with a microcontroller. The results of temperature and relative humidity are validated by sizing the cooling capacity and volume by a factor of 10 times. The cooling capacity of the designed refrigerated system is greater than the sizing factor by 10 times so we can get even better temperature control.

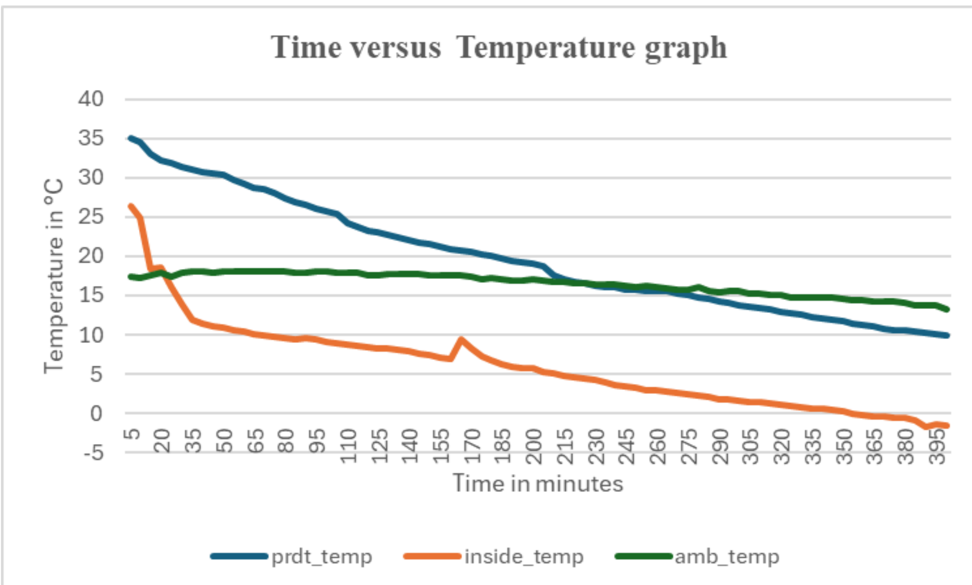

Figure 4. 7: Time versus temperature graph

Figure 4.6 shows the trend of temperature for 40 liters water product, the temperature of inside air and the temperature of outside air. The Graph shows that the water takes about 6 hours and 40 minutes to decrease the temperature of water from 35°C to 8°C, the also shows the inside cold storage and ambient temperature trend with time.

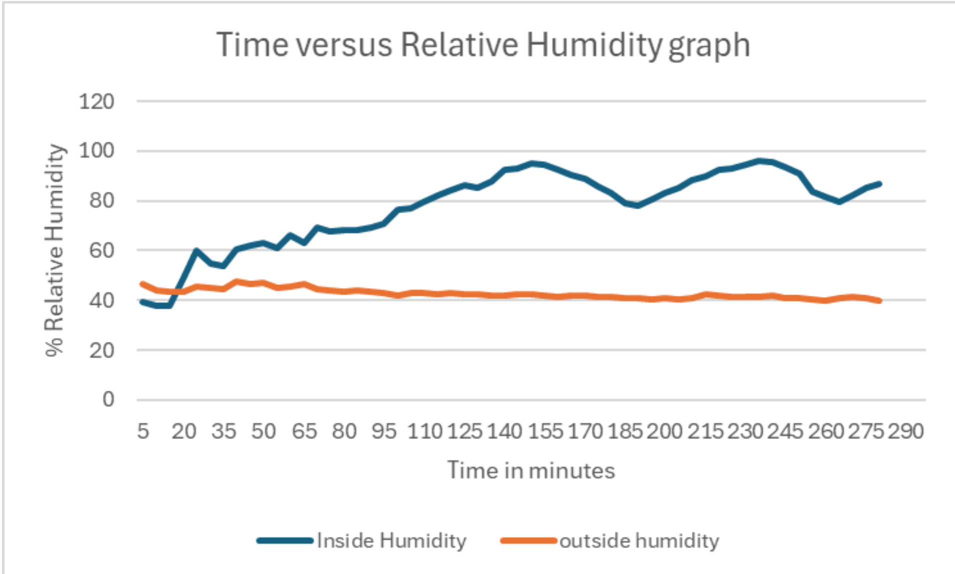

Figure 4. 8: Inside and outside relative humidity graph

The temperature and relative humidity are controlled as a result of software and hardware. Figure 4.7 showed that the design of cold storage system precisely controls the relative humidity.

The system provided reliable data about inside/outside temperature and humidity as shown in Figure 23 and Figure 24, respectively. The system also provides information about electrical power that is generated by solar panels, the power consumption by cold storage, the power that is stored in the battery for backup and sending the necessary signals in case of any emergency on real-time data. As a result, the cold storage-maintained quantity for extended period of time as well as maintained high-quality attributes of vegetables and fruits during storage. This modification makes it possible to remotely manage cold storage facilities due to solar-powered applications.

4.5 Conclusion:

The IoT based, solar-powered cold storage unit system of volume $1.2m^3$ is designed with storage capability of 500kg of tomatoes, to provide a reliable, efficient, and user-friendly operation. It consists of advanced electronic components and sophisticated software logic to ensure that perishable goods are stored under optimal conditions, thereby reducing waste and improving the viability of solar-powered refrigeration for remote and off-grid locations. The results obtained from this study are given below.

1. Cooling load is calculated considering transmission load, infiltration load, product load, respiration load and internal loads. 765 watts are calculated including 10% of safety factor.
2. Based on calculated cooling load appropriate refrigeration equipment is selected and designed to fulfill the requirement.
3. Temperature distribution along wall and cold storage is analyzed. With one side surface temperature of 100mm polyurethane at 45°C the heat transfer is kept such that the other surface is at approximately 10°C.
4. The solar powered cold storage system can achieve required temperature and humidity which prevents the food quantity from being lost and prevents the loss of nutritional quality for prolong period of time. The design refrigerated system can be used for multiple products.

Remote monitoring of temperature and relative humidity makes it possible to improve and control the quality of the products. As the demand for cold storage increases, automation is imperative to control vital factors. Incorporation of new technologies can greatly assist in monitoring the beneficial effects in real time and significantly enhancing food products benefiting humans.

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