COOLING EFFICIENCY: ANALYZING COOLING RATES AND RECOVERY TIMES IN A COLD ROOM LOCATED IN HVAC LABORATORY

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Faculty of Mechanical Technology and Engineering

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A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering Technology (Refrigeration and Air Conditioning System) with Honours

Faculty of Mechanical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this Choose an item. Entitled “Cooling Efficiency: Analyzing Cooling Rates and Recovery Times in A Cold Room Located in HVAC Laboratory” is the result of my own research except as cited in the references. Choose an item. Has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : SEELLANN A/L M. GUNASAGRAN

Date : 10/1/2025

APPROVAL

I hereby declare that I have checked this thesis, and, in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Refrigeration and Air Conditioning System) with Honours.

Signature : ....

Supervisor Name : M O H D F A E Z B I N Z A I N O L

Date : 10/1/2025

DEDICATION

I devote my dissertation work to my family and friends. A special feeling of gratitude to my loving parents, Mr. Guna and Mrs. Shanti, whose scarifies time and vitality to raise meas a son, a student, and a future. My sister and brother Mogana and Seridran never left myside when I needed help at most. I also dedicate this dissertation to my friends who supported me throughout my living, studying, and maturing. I will always appreciate all they have done, especially teachers, lecturers, and lab assistant for helping me in the development of my technological skills, Mr. Mohd. Faez bin Zainol for the many hours of proofreading, supervising and guidance. I dedicate this work and give special thanks to my friend Lee Chun and my wonderful roommate Faisal for being there for me throughout the entire bachelor's degree program.

ABSTRACT

This study investigates the performance evaluation of an air conditioning system following the ISO 5151 standard. The research highlights the challenges faced by non-commercial entities, such as universities and individual users, in conducting such evaluations due to the high costs associated with specialized facilities, equipment, and calibration processes. These resources are often limited and expensive, making them inaccessible to many. To address this, the study adopts a methodology that leverages a laboratory chamber designed to simulate the functionality of an ISO 5151-compliant testing environment. The chamber's thermostat was set to 20°C and 27°C for dry bulb temperatures, aligning closely with the ISO 5151 standard of 27°C. However, a key limitation of this approach was the inability of the chamber to control wet bulb temperature, which is a critical parameter in ISO 5151 testing. The experimental setup involved testing a cold room with specifications including the use of R-410A refrigerant, an inverter system, and a total volume of 4.3218 m^3. The cold room was evaluated under two scenarios: with and without simulated load conditions. The results revealed that both the 20°C and 27°C thermostat settings yielded a consistent cooling performance efficiency of 33.65%. The findings of this research demonstrate that laboratory chambers can serve as viable alternatives for assessing the cooling capacity of air conditioning units, particularly for non-commercial applications. This approach offers a cost-effective solution for performance evaluation while adhering to the principles of the ISO 5151 standard. The study concludes that despite certain limitations, such as the inability to regulate wet bulb temperature, laboratory-based testing provides valuable insights into the cooling performance of air conditioning systems.

Keywords: Air conditioning performance, ISO 5151 standard, laboratory chamber testing, cooling capacity, thermostat settings, dry bulb temperature, wet bulb temperature limitation, R-410A refrigerant, inverter system, simulated load, non-commercial applications.

ABSTRAK

Kajian ini menyiasat penilaian prestasi sistem penyaman udara mengikut piawaian ISO 5151. Penyelidikan ini menekankan cabaran yang dihadapi oleh pihak bukan komersial, seperti universiti dan pengguna individu, dalam menjalankan penilaian sedemikian disebabkan oleh kos tinggi yang berkaitan dengan kemudahan khusus, peralatan, dan proses penentukuran. Sumber-sumber ini selalunya terhad dan mahal, menjadikannya sukar dicapai oleh ramai pihak. Untuk menangani isu ini, kajian ini menggunakan metodologi yang memanfaatkan makmal yang direka untuk mensimulasikan fungsi persekitaran ujian yang mematuhi ISO 5151. Termostat bilik makmal disetkan kepada suhu mentol kering 20°C dan 27°C, sejajar dengan piawaian ISO 5151 pada suhu 27°C. Walau bagaimanapun, satu had utama pendekatan ini adalah ketidakupayaan bilik untuk mengawal suhu mentol basah, yang merupakan parameter penting dalam ujian ISO 5151. Tetapan eksperimen melibatkan pengujian bilik sejuk dengan spesifikasi termasuk penggunaan refrigeran R-410A, sistem inverter, dan jumlah isipadu sebanyak 4.3218 m^3. Bilik sejuk dinilai dalam dua senario: dengan dan tanpa keadaan beban simulasi. Keputusan menunjukkan bahawa tetapan termostat pada suhu 20°C dan 27°C memberikan kecekapan prestasi penyejukan yang konsisten sebanyak 33.65%. Penemuan penyelidikan ini menunjukkan bahawa makmal boleh menjadi alternatif yang boleh diterima untuk menilai kapasiti penyejukan unit penyaman udara, terutamanya untuk aplikasi bukan komersial. Pendekatan ini menawarkan penyelesaian kos efektif untuk penilaian prestasi sambil mematuhi prinsip-prinsip piawaian ISO 5151. Kajian ini menyimpulkan bahawa walaupun terdapat had tertentu, seperti ketidakupayaan untuk mengawal suhu mentol basah, ujian berasaskan makmal menyediakan wawasan yang berharga mengenai prestasi penyejukan sistem penyaman udara.

Kata Kunci: *Prestasi penyaman udara, piawaian ISO 5151, ujian makmal, kapasiti penyejukan, tetapan termostat, suhu mentol kering, had suhu mentol basah, refrigeran R-410A, sistem inverter, beban simulasi, aplikasi bukan komersial.*

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I want to express my heartfelt gratitude to all those who have contributed to my researchand supported me throughout my journey. First and foremost, I would like to thank God,the Most Gracious and the Most Merciful, for blessing me with the strength, patience, and guidance to complete this study.

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I would also like to express my gratitude to my friends and colleagues for their support, motivation, and valuable discussions. Their presence and encouragement have made this research journey more enjoyable and meaningful. To my beloved parents, I am eternally thankful for their unconditional love, continuousencouragement, and unwavering belief in my abilities. Their sacrifices and prayers have been my greatest source of strength and inspiration throughout this process. Lastly, I would like to acknowledge and thank all the individuals who have aided, whether in the form of guidance, technical support, or inspiration. Your contributions have been instrumental in shaping the outcome of this research.

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LIST OF SYMBOLS AND ABBREVIATIONS

HVAC	-	Heating, Ventilation, and Air Conditioning.
PCB	-	Printed Circuit Board
ANN model	-	Artificial neural network model
ML	-	Machine Learning
DL	-	Deep Learning
HVDC	-	High Voltage Direct Current
COP	-	Coefficient of Performance
(°C)	-	Celsius
(s)	-	Second

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Cooling efficiency is a critical consideration within HVAC systems, particularly in environments like laboratories, pharmaceutical storage facilities, and food processing plants,where precise temperature control is imperative. The efficacy of cooling systems directly impacts energy usage and the preservation of product integrity. Therefore, this studyinvestigates the recovery durations and cooling rates of a cold room that is part of an HVAClaboratory.

HVAC systems, which include heating, ventilation, and air conditioning, are essential for preserving the quality of items that are sensitive to temperature in a variety of industries, such as food processing plants, pharmaceutical storage facilities, and laboratories (US EPA, 2014). A specialist subset of HVAC systems, cold rooms are engineered to maintain constant low temperatures and are vital for controlled environmental research as well as the preservation of perishable items (Calati et al., 2022).

As important as it is to evaluate the cooling capacity of HVAC systems, there is still a largeamount of information missing when it comes to accurately analyzing cooling rates and recovery times, especially in HVAC lab environments (Asim et al., 2022). This disparity makes it difficult to accurately assess the efficacy of cooling systems and to apply focused interventions aimed at improving system performance.

As Consequence, poor energy use is common and temperature-sensitive laboratory procedures are put at danger. This study methodically assesses a cold room's cooling efficacy in an HVAC laboratory setting in light of these difficulties. Through careful measurement of cold room performance indicators in a range of operating environments, this study aims to offer significant insights for improving cooling system maintenance, operation, and design.

1.2 Problem Statement

There exists a significant knowledge gap concerning the cooling effectiveness of HVAC laboratory settings, specifically regarding the thorough understanding of cooling rates and recovery times of cold rooms (Amir et al., 2024). Cold rooms are essential for keeping thingsat the consistent temperatures needed for a variety of tasks, such as storing perishable commodities and carrying out accurate research. Comprehensive data on the rate of temperature recovery from temperature changes and the rate at which cold rooms can reach the target temperature are lacking, which makes it difficult to accurately evaluate the overallefficacy of cooling systems in HVAC laboratories.

The lack of accuracy of determining cooling efficiency restricts the execution of specific measures meant to improve system performance and lower energy usage. Moreover, it putstemperature-sensitive laboratory procedures at risk and adds to energy waste. (LINSAD, 2024) In HVAC laboratory settings, preserving temperature-sensitive materials and experiments, maximizing energy savings, and maximizing cooling system performance all depend on resolving this dearth of thorough data on cooling rates and recovery times.

1.3 Research Objective

The objectives of this research are as follows:

- **i.** To determine the cold room's cooling rate experimentally under a range of operating circumstances and outside influences, with the goal of maximizing energy efficiency and performance using a carefully thought-out experimental setup and reliable data collection techniques.

- **ii.** To evaluate, through variable studies, the impact of changing external environmental conditions, such as ambient temperature and humidity, on the cold room's cooling rate.

- **iii.** To conduct experiments quantifying the impact of door opening frequency on the cooling rateof the cold room.

1.4 Scope of Research

The scope of this research encompasses the following key components:

i. **Experimental Setup:** testing to determine how quickly the cold room cools and recovers. Thisentails creating and putting into action an experimental setup that precisely records pertinent variables and circumstances.

ii. **Data Collection:** Collecting data methodically during tests to measure and assess recovery times, cooling rates, and other relevant factors. To guarantee the accuracy and reliability of the data gathered, this entails putting in place reliable data collection techniques.

iii. **Variable Studies:** examining a range of variables and components, including airflow, equipment performance, insulation quality, and operating conditions, that affect the efficiencyof cooling. To find patterns and correlations in the gathered data, variable studies must be carried out.

iv. **Evaluation of Performance:** Examining the cold room's performance in various operating conditions to determine its limits and capabilities. Analyzing the cold room's ability to maintain temperature stability under different conditions is part of this.

v. **Recommendations for Improvement:** Determining conclusions from the research and offering feasible recommendations to improve cooling effectiveness. In order to suggest workable solutions for enhancing system performance and energy conservation, the results must be synthesized.

1.5 Limitations

i. **Limited Scale:** An example of a small-scale system is the refrigerator that serves as the coldroom. The findings might not apply to bigger, commercial cold rooms with various layouts and configurations.

ii. **Single Data Acquisition System:** There is a chance of a single data acquisition system goingdown. Data dependability may be increased by using a backup system.

iii. **Limited Adjustments for External Conditions:** It's possible that the experiment won't be ableto replicate all the variations in outside temperature and humidity that a real-world cold roomwould experience.

iv. **Sensor Positioning**: It's possible that some temperature variations in the cold room are not picked up by the sensors. An even more complete picture could be obtained with micro sensor alternative positioning techniques.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cooling efficiency is a key component of HVAC systems, particularly in environments where precise temperature control is essential, such as laboratories, pharmaceutical storage facilities, and food processing industries. Cold rooms are specialized areas inside HVAC systems that are necessary to consistently maintain low temperatures for a variety of applications, such as the storage of perishable goods and controlled environmental research.Cooling efficiency considers factors such as energy efficiency, affordability, and ecological responsibility in addition to temperature management. Effective cooling operations are crucial for preserving product quality, reducing energy use, and saving operating costs for companies to meet objectives regarding sustainability and regulatory requirements.

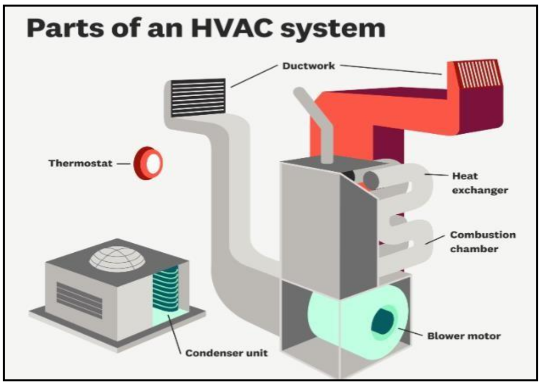


Figure 2.1 Parts of an HVAC System

(https://www.angi.com/articles/hvac-system-parts.

Figure 2.1 Parts shows parts of an HVAC System. Even while cooling performance is crucial, there are obstacles to overcome, including insulation quality, machinery efficiency, and external environmental variables, all of which can lead to operational drawbacks and delays. These problems need to be fixed to increase cooling efficiency and fully utilize the benefits of HVAC systems. Technological advancements drive development in HVAC systems, necessitating in-depth analyses of cooling performance. To identify problem areas and implement targeted interventions, investigation is needed to evaluate cooling rates, recovery times, and overall system efficiency. By understanding the factors that affect cooling efficiency, businesses may enhance the design, operation, and maintenance protocols of their cooling systems. The research's major objective is to analyzethe cooling effectiveness of a cold room in an HVAC application laboratory by conducting experimental studies in addition to temperature and airflow distribution assessments. By providing insights into HVAC system performance under controlled conditions, the goal is to enhance HVAC technology and optimize cooling operations across a range of application.

2.2 Cooling Efficiency in HVAC Systems

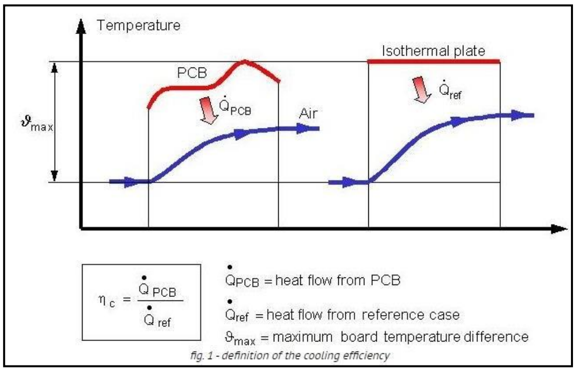


Figure 2.2 Definition of Cooling Efficiency

The term of cooling efficiency is shown in Figure 2.2. Hundreds of projects have demonstrated the efficacy of this idea, which has been applied for over a decade. Though a tiny percentage of thermal designers still use it, it is considered a fundamental idea in their field. The ratio of the heat that may be removed through a Board and the reference case is known as the cooling efficiency. A perfectly smooth temperate paralleled plate case with an ambient temperature degree that matches the PCB plate's highest temperature is referred to as the case for reference (figure 2.2).

The cooling efficiency of HVAC systems is critical to maintaining the quality of products that are temperature-sensitive and ensuring indoor comfort in a range of conditions. The ability to control and keep precise degrees is crucial in environments such as laboratories, pharma storage facilities, and food manufacturing industries, where even small fluctuationsin temperature have the potential to compromise the quality and safety of products. Numerous prior studies have emphasized the need of optimizing energy economy and preserving product integrity through efficient cooling operations. For instance, study resultsfrom the US EPA, or Environmental Protection Agency, emphasizes the need of energy- efficient HVAC systems in minimizing environmental effect and reducing energy usage. Ina similar vein, studies conducted by Seraj et al. (2024) have demonstrated the significance of cooling efficiency in preserving product quality and safety in pharmaceutical facilities. Besides saving energy, sustainable and economical methods depend on efficient cooling techniques. By reducing energy use and operating costs, organizations can both significantlyreduce their environmental footprint and save money. This supports the overall goals of ecological responsibility and governmental compliance and highlights the need for continuous development in HVAC system cooling efficiency.

Furthermore, as air conditioning technology has advanced, enhancing cooling efficiency hasbecome more crucial to address evolving needs and issues. Research by DeQuante Rashon Mckoy et al. (2023) suggests that a variety of aspects, such as equipment performance, insulation quality, and external environmental variables, may have an impact on cooling effectiveness. It is crucial to understand and take care of these factors tooptimize the benefits of HVAC systems and enhance cooling efficacy. The discussion surrounding the cooling efficiency of HVAC systems typically highlights how important it is to maintain the comfort of interior spaces and temperature-sensitive commodities. It ispossible to emphasize the need of preserving product integrity and maximizing energy consumption by referencing past studies that situate the importance of cooling efficiency within the broader framework of HVAC system performance and ecology.

2.3 Cold Room Operations and Cooling Effectiveness

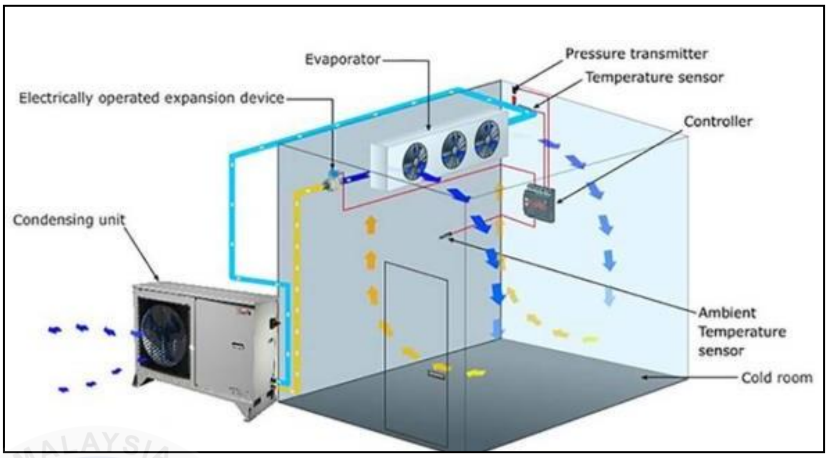


Figure 2.3 Air flow inside of cold room

(https://www.danfoss.com/en/service-and-support/case-stories/dcs/cold-storage-room-what-you-need-to-know-about-refrigeration-part-2/)

Figure 2.3 depicts the airflow in the cold room's side. Cold room operations are essential in many industries, including medications, food processing, and research into science, where precise temperature control is required for product quality and safety. Understanding the variables that affect how well cold room cooling works is crucial to preserving the integrity of temperature-sensitive items and streamlining processes. The degree to which cold rooms cool is largely dependent on the quality of the insulation. Good encapsulation is required to keep the cold room consistently cold and to reduce heat transfer. Studies by researchers suchas Mercier et al. (2017) have highlighted the importance of insulating substances and their impact on cooling efficiency. Changes in temperature and energy loss due to inadequate insulation might jeopardize the quality of the item and increase operational costs.

Equipment effectiveness is another crucial factor that has a big impact on cooling efficacy. The reliability and effectiveness of the airflow, refrigeration, and temperature control systems have a major influence on the efficacy of cold rooms. Equipment optimization maintenance and optimization are two crucial strategies for increasing cooling efficiency in cold room operations, according to study by Andrii Sazanskyi & Mykhailo Khmelniuk (2023). Regular maintenance and enhancements that maximize system efficiency and lower energy consumption can lead to improved cooling efficacy. The state of the outside environment has an impact on how well cold rooms cool. Variables including humidity levels, ventilation patterns, and ambient temperature might affect cold rooms' ability to maintain desired temperature levels. Cong et al.'s 2019 investigations address challenges posed by external weather conditions and the need for adaptable cooling methods to decrease their impact. By understanding climate-related challenges and implementing appropriate solutions, organizations can improve the overall efficiency of cold room operations.

There is a lot of material in the literature regarding the challenges of achieving the best possible cooling efficiency in cold rooms. M. Hassan and colleagues' (2016) research uncovered several issues, including inadequate insulation, outdated equipment, and less-than-optimal operating practices. To solve these problems, a thorough plan that considers factors including insulation quality, equipment performance, and weather conditions is required. By addressing these problems, organizations may increase cooling efficiency, use less energy, and ensure the integrity of temperature-sensitive goods stored incold rooms.

2.4 Utilization of Cold Rooms

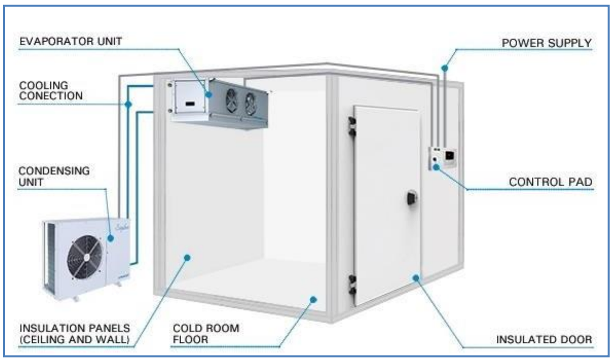


Figure 2.4 Cold Room

(https://www.intarcon.com/en/types-of-cold-rooms/)

Figure 2.4 lists the requirements for a cold room. Since cool rooms offer the required refrigeration to preserve perishable commodities and ensure perfect storage conditions, theyare an essential piece of equipment in many sectors. Understanding the various uses for coldrooms may improve your comprehension of their vast array of uses. Because of their usefulness and effectiveness, cold storage rooms are necessary for warehouses, eateries, foodprocessing facilities, and pharmaceutical storage units. There are more uses for cold rooms than simply preservation in the modern, fast-paced business world. Product handling,consumer accessibility, and inventory control are some of its crucial components. Modern cold rooms are constructed with features that increase accessibility, cleanliness, and overall operational efficiency. The ease with which customers can now reach items stored in cold rooms, for instance, could lead to increased convenience and sales.

2.5 Considerations When Choosing a Cold Room

Figure 2.5 Requirements to choose a cold room

(https://www.linkedin.com/pulse/16-basic-requirements-cold-storage-installation-can-liang**)**

The specifications for selecting a cold room are shown in Figure 2.5. Selecting a cool roomfor specific storage needs requires thoughtful evaluation of a number of factors in order to obtain the highest possible performance and operating economy. Among these elements are:

i. Temperature Control: Evaluating the cold room's capacity to maintain the appropriatetemperature ranges consistently Size and Capacity: Establishing the size and capacity of the cool room to suitably handle the required amount of storage and product requirements.

ii. Energy Efficiency: To reduce running expenses and environmental impact, consider the cold room's energy efficiency, including insulation quality and equipment performance.

iii. Regulatory Compliance: Ensuring compliance with relevant laws and rules governing the storage of specific goods, including food or prescription drugs.

iv. Accessibility and Convenience: To optimize retrieval and storage processes and increase operational effectiveness, components such as design, availability, and user convenience are evaluated.

2.6 Summary or Research Gap

A thorough examination of a study done to assess the chilling capabilities of a cold storage system used in the pharmaceutical business is given in the review of the research (Sularno et al., 2018). The goal of this study was to gain a thorough understanding of the cold storage'stemperature distribution, which is a crucial component that affects the quality of products kept in pharmaceutical storage facilities. Through a combination of numerical simulation and experimental measurement methods, the study investigated different facets of the cooling effectiveness of cold storage. Thermocouple sensors were used in experimental investigations to quantify cooling rates and air temperature dispersion. The cold storage facility itself was described as of the ceiling type and having an R22 refrigerant- powered vapour compression refrigeration mechanism.

Featuring an established maximum temperature of 5°C, it was intended to maintain temperatures between 2°C to 8°C, which is critical for storing 24 liquid vaccine bottles. To maximize cool air flow and ensure worker access, several bottle and rack configurations were examined. Ansys Fluent software was used in the study's numerical simulation section to create a temporary multifaceted computational fluid dynamics (CFD) model. To accurately replicate real-world settings, our model approximated heat conduction within the bottles and took into account avariety of boundary variables, including external temperature and heat transfer coefficients (Barbhuiya et al., 2024). The conclusions about the distribution of temperatures, cooling rates, and the efficacy of various bottle and rack configurations were provided in the resultsand comments section. The performance parameters for each arrangement were displayed ingraphs and tables, which showed that some arrangements produced a more even temperaturedistribution and faster cooling times. Crucially, a comparison of the outcomes of the numerical and experimental simulations showed a high degree of agreement, confirming thesimulation method's efficacy in forecasting heat transfer processes. The study's findings stressed the importance of bottle and rack layouts on how well pharmaceutical facilities' coldstorage systems cool. It demonstrated the value of computational modeling as a forecastingtool and offered suggestions for maximizing cooling effectiveness in these kinds of settings. This study adds important information to the continuing efforts in pharmaceutical cold roomenvironments to maintain product efficacy and purity.

The goal of Naveen et al.'s 2017 temperature mapping study on a cold room was to evaluatethe chamber's temperature distribution and compliance with predetermined standards. Temperature and humidity data loggers, made by Kaye RF Val Probe, were placed at eighteen different points in the room to track changes in temperature. The acceptable standards stipulated that the temperature must be kept between 2°C and 8°C, which is essential for the storage of items sensitive to temperature changes and pharmaceutical products. We looked at several factors that affect cold room performance, such as the outside temperature, the length of time a door is opened, power outages, airflow velocity, and thermal load. Mapping the chamber while it was empty and mapping the room after it was filled with material were the two primary stages of the investigation in order to guarantee temperature stability, each phase included a "come up" study, power outage and recovery tests, and opening the doors and recovery investigations (Nicholas H et al., 2021). The cold room effectively kept temperature ranges under various circumstances, with acceptable times for recuperation and temperature changes. In order to evaluate the system's durability, worst-case situations including prolonged door opens and power outages were also replicated. All things considered, the study offered insightful information about how well cold rooms function, guaranteeing the secure storage of products that are sensitive to temperature in medicinal settings.

The authors of the paper "Energy efficient HVAC systems," (Jouhara & Yang, 2018), stress how important it is to improve the layout and functionality of HVAC (heating, ventilation, and air conditioning) systems in buildings in order to attain energy efficiency. In order to lower building energy use, the authors stress the importance of optimizing the different integrated electrical and mechanical parts of HVAC systems. They note that in many industrialized nations, buildings account for more than 40% of total power use, which makes installing effective HVAC systems essential for energy conservation. The goal of the energy-efficient HVAC systems special issue was to compile new and creative studies that would advance our knowledge of energy-efficient HVAC systems on a scientific and technical level. Heat pumps, water heating and cooling systems, effective conditioning systems, element designs, battery storage, and process regeneration were only a few of the many subjects covered in the entries. The authors further point out that fascinating articles on additional aspects of HVAC management and systems were also submitted, indicating the breadth of subjects addressed by this body of work.

Nasif et al.'s article "The boundary energy converter in HVAC energy retrieval systems: Techniques energy analysis" examines the heating capacity of an enthalpy/membranethermal transfer device (2020). Kraft paper serves as a medium for the passage of heat and moisture in HVAC energy recovery systems. Temperature and water content studies in the lab are used to determine the acceptable, hidden, and total effectiveness of the heat exchanger. Additionally, the annual energy consumption of an air conditioner with an enthalpy/membrane heat exchange is analyzed and compared with a conventional climate control cycle using customized HPRate software. Introduction emphasizes how energy recovery systems are becoming more and more crucial to HVAC systems because of the growing need for improved indoor air quality and the resulting rise in building cooling and heating loads. The use of porous membranes in enthalpy heat exchangers has several benefits, including low complexity, moving part-free static operation, and effortless integration with current air conditioning systems.

A summary of earlier investigations on membrane heat exchangers, both theoretical and experimental, shows that latent recovery can result in significant energy savings. The article summarizes several research evaluating membrane heat exchangers' energy efficiency under various environmentalcircumstances. This research consists of theoretical thermodynamic modeling, computer simulations, experimental tests, and performance assessments with the aid of programs likeHPRate and EnergyPlus. This article describes the improved HPRate code that makes it possible to model air conditioners with both latent and sensible heat recovery heat exchangers. This modeling allows for insights into the annual energy consumption and transient operational states of these systems. All things considered, the paper offers insightful information about the thermal efficiency and possible energy savings of membrane heat exchangers in HVAC energy recovery systems. It is an invaluable resource for this kind of research because of its thorough analysis, experimental validation, and comparison to traditional systems.

The article "Energy preservation in room air conditioning units by recovering cold energy from condensate" (Nethaji et al., 2019) examines a novel strategy for room air conditioningsystem energy conservation by making use of the cold energy found in split air conditioner condensate drips. The condensate temperature can range from 10°C to 15°C in areas with high relative humidity, such as tropical nations, offering a considerable cooling potential. Inorder to efficiently absorb heat from the walls and lower the infiltration load, the study suggests circulating this condensate along the inside walls of the space through copper tubes.By pre-cooling the return air from the room, this procedure shortens the air conditioning system's runtime and, in turn, lowers energy usage.

The study entails a thorough examinationof the impacts of condensate-based wall cooling on a range of factors, including wall humidity, the efficiency of the air conditioning system, supply and return air temperatures, energy usage, humidity reduction and and thermal comfort. Condensate is pumped through copper tubes installed into the wall of the room as part of the experimental setup. No additional energy is needed for pumping because gravity is helping the flow. The cooling process is finished when the heat-laden condensation is released into drains following circulation. The study emphasizes how wall cooling using condensate can save up to 8% of energy, which can lower energy costs and increase the energy capacity of room air conditioners. Further improving the system's overall performance is the pre-cooling of the returned air by cold condensate, which also improves thermal comfort and dehumidification.The goal of the research is to show how this innovative method of energy conservation andimproved room comfort in air conditioning operations works through in-depth analysis andtesting.

The paper "Sustainability of Heating, Ventilating and Air-Conditioning (HVAC) Systems inBuildings" (Asim et al., 2022) offers a thorough analysis of a number of factors related to HVAC system sustainability. It starts off by pointing out how important

HVAC systems areto preserving indoor comfort and air quality while also recognizing how much energy they use on a worldwide scale. The topic then shifts to methods for improving HVAC systems' energy efficiency, such as waste heat recovery, sophisticated design and control techniques,and the use of renewable energy sources. The essay also highlights the significance of HVAC systems and indoor air quality in reducing microbiological contamination, especially in lightof previous pandemics like COVID-19. In this context, a variety of air purification technologies and infection control measures are investigated. Furthermore, condensaterecovery from HVAC systems is investigated as a potentially useful water resource, with a focus on appropriate treatment to avoid microbiological contamination.

The necessity of modifying current HVAC systems to increase sustainability is also covered in the paper, with particular attention paid to techniques like duct leak repair, smart monitoring and control systems, and the incorporation of renewable energy sources. The paper concludes byhighlighting the critical requirement of developing and upgrading sustainable HVAC systems and emphasizing how crucial it is to optimize sustainability in decision-making processes by taking into account variables like building kinds, climate, and occupant health.

The study "Review of Predictive Maintenance Algorithms Applied to HVAC Systems" by Niima Es-sakali et al. (2020) looks at the application of predictive maintenance (PdM) approaches for HVAC systems. Predictive maintenance reduces maintenance costs and boosts dependability by avoiding both unnecessary preventative maintenance andunscheduled reactive maintenance by employing online assessments of health to forecast equipment failures.

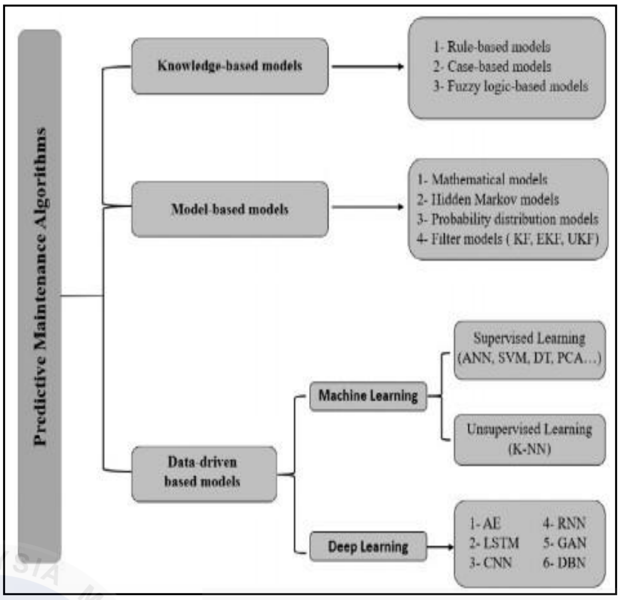


Figure 2.5 Predictive maintenance algorithms (Niima Es-sakali et al 2020

When employing predictive maintenance, there are several methods to consider, such as data-driven approaches, physical-based model methods, and based on information methods, as shown in Figure 2.5. In addition to the single-based ways stated, there are othermixed methods as well, such as cloud-based, fleet-based, IoT-based, Artificial Learning- based, and time-based. The authors categorize the three main types of PdM algorithms for HVAC systems into knowledge-driven, model-based, and data-based methods following a comprehensive review of the literature. The accuracy and application of knowledge-based models, which are dependent on expert rules and historical fault data, are limited in complexsystem environments. Model-based strategies use computational and physical models to predict the lifespan of devices and diagnose faults, while data-driven models, particularly those that are based on machine learning techniques alongside thoroughly learning, analyzesensor data to estimate failures and choose them for their ability to handle extremely dimensional data and demonstrate hidden patterns.

The analysis emphasizes how combining several predictive models can improve forecast reliability and accuracy. Notwithstanding the progress made, many obstacles continue to exist, including the lack of data accessibility, intricate operational circumstances, and fluctuations in algorithmic performance. The authors suggest hybrid methods for better predictive maintenance results in HVAC systems, which incorporate several ML and DL models. In conclusion, by precisely anticipating breakdowns and streamlining maintenance schedules, predictive maintenance powered by developments in IoT and AI offers major advantages for HVAC systems. Nevertheless, further study and the creation of more reliable, hybrid predictive models are required due to the complexity and unpredictability of these systems.

Given the substantial energy usage connected with cold shops, the research by (J.A. Evans et al., 2021) provides insightful information about enhancing the energy performance of these establishments. By means of 28 audits carried out around Europe, the researchers pinpointed common deficiencies and suggested strategies to improve energy efficiency. Remarkably, potential energy savings of up to 72% were found, mostly through retrofittingenergy-efficient technologies, fixing existing equipment, and optimizing retail utilization. These enhancements frequently had quick payback periods, demonstrating their financial sustainability. The results highlight how crucial it is to perform routine system inspections and automated monitoring to quickly detect and fix inefficiencies. Estimate the potential energy savings. Insummary, the study highlights the noteworthy prospects for energy conservation in coldstorage facilities.

The notion of the Coefficient of Performance (COP) and its importance in assessing theefficiency of heat pumps and air conditioning systems are explored in depth in the study by(Nikhilesh Mukherjee 2023).

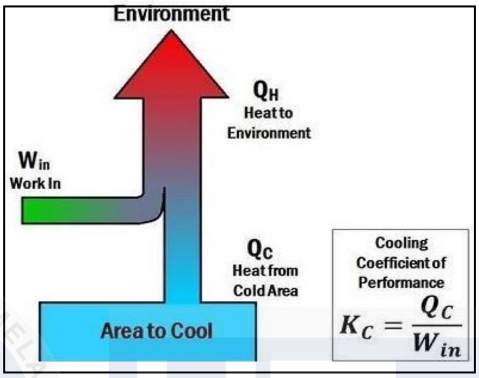


Figure 2.6 COP for heating and cooling (Nikhilesh Mukherjee, 2023).

The coefficient of performance (COP), a crucial indicator of heat pump and air conditioning system efficiency, is displayed in figure 2.6 above. When it comes to instantaneousperformance, COP is different from efficiency ratings as it shows the ratio of heat generatedto electrical power input. Heat transfer is the intended output in freezer and air conditioning,hence this metric is essential. There are separate COPs for cooling and heating, with the former reflecting the ratio of heat removed to work done by the compressor, and the latter accounting for both heat removal and compressor work. While COP values vary based on system type and operating conditions, vapor compression systems typically exceed 1 due to their efficient conversion of work into heat. Refrigerators, for instance, have a maximum COP influenced by ambient and internal temperatures. In contrast, the COP of heating is always greater than 1, reflecting the heat rejected to the hot sink. Different systems, like adsorption, may exhibit high COPs due to their operational principles. COP is closely relatedto Carnot efficiency, with maximum values determined by temperature differentials. Understanding COP is crucial for optimizing HVAC system efficiency, leading to energy savings and environmental benefits.

The temperature mapping study of cold rooms by (UNICEF, 2020) is vital for ensuring vaccines are stored safely within the recommended temperature ranges. It establishestemperature distribution, confirms compliance with storage requirements, and identifies performance gaps. The WHO emphasizes its importance, yet implementation remains low in low- and middle-income countries. To address this, the WHO-UNICEF Hub developed aguide and software tool to simplify mapping. Case studies highlight its impact: confirming compliance in existing cold rooms and identifying issues in new installations. Despite its importance, more guidance and user-friendly tools are needed to facilitate implementation, ensuring vaccine quality and safety.

In their review, (Simpeh et al., 2021) address the pressing issue of energy consumption by HVAC systems in buildings. Through a systematic literature review, they identify key practices for enhancing energy efficiency in these systems, especially in developing countries. Their findings highlight various measures, from low-cost options like system tuning to more significant investments in smart technologies. They emphasize the significance of incorporating vegetal systems into buildings and using human-centered techniques. In order to help experts and encourage efficiency from the outset of construction, they practically advise embedding energy efficiency methods into building rules. Their suggested integrated optimization methodology provides creative ways to close gaps in energy efficiency. All things considered, the research offers insightful information about how to improve HVAC system energy efficiency, with implications for building codes and environmentally friendly building techniques.

The article offers a thorough analysis of numerous technologies and strategies targeted at raising the HVAC systems' energy efficiency. It addresses the significance of lowering HVAC systems' energy usage in light of growing fossil fuel prices and environmental concerns. The study examines many approaches, including the impact of building behavioron energy consumption and the use of evaporated cooling systems, ground-coupled HVACsystems, thermal storage systems, and heat recovery systems. Fernandez-Seara et al. conducted an experimental analysis on an air-to-air heat recovery unit for residentialdwelling ventilation systems that was outfitted with a sensible polymer plate heat exchanger.Figure 2.7 depicts their system's layout with the heat recovery unit.

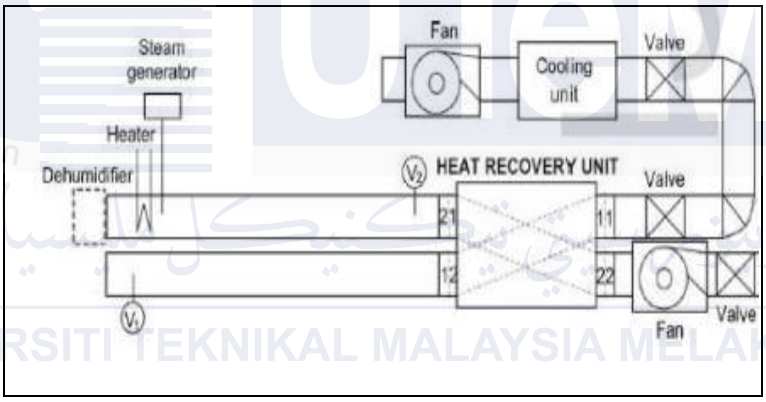


Figure 2.7 Layout of the experimental facility of the heat recovery uni t(Fernandez-Seara, 2021)

One notable strength of the article is its detailed examination of each energy-saving strategy,including descriptions of technologies, previous studies' findings, and potential energy- saving impacts. However, it does not delve deeply into the specific challenges or limitationsassociated with each approach, which could be considered a weakness. The article's notable features include its focus on practical solutions for improving HVAC energy efficiency and its relevance for addressing environmental concerns and rising energy costs.

The study explores the utilization of nano-refrigerants, specifically Al2O3 nanofluid, in domestic refrigerators to enhance thermodynamic efficiency and reduce energy consumptionby (Sarrafzadeh Javadi & Saidur, 2021). Investigating stability, thermodynamic performance, and energy efficiency, the research fills a gap in understanding the applicationof nanofluids in refrigeration systems. Results indicate that while low concentrations of nanoparticles exhibit long-term stability, higher concentrations face challenges, emphasizing the need for alternative preparation methods. The general temperature was regulated throughout the studies, as seen in Figure 2.8, and it always followed the same pattern. Additionally, relative humidity was regulated within the recognized bounds of the global norm.

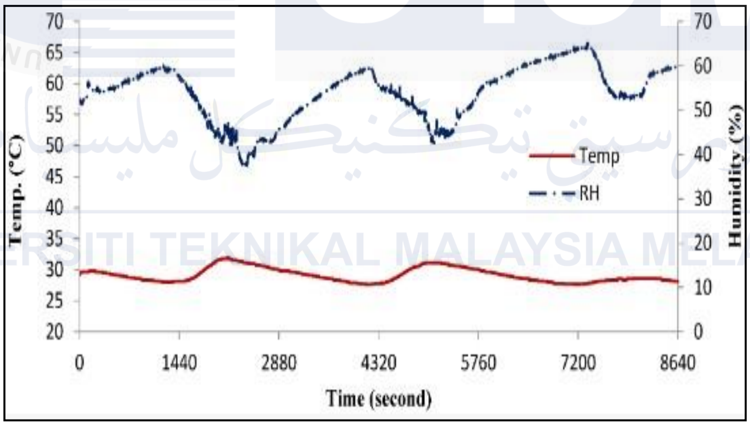


Figure 2.8 Ambient temperature and relative humidity of test room during experiments.(Sarrafzadeh Javadi & Saidur, 2021).

Nano-refrigerants demonstrate improved heat transfer, evidenced by an increased evaporator temperature gradient, suggesting enhanced thermodynamic behaviour. Moreover, incorporating Al2O3 nanoparticles leads to a notable reduction in energy consumption, witha decrease of 2.69% observed compared to conventional refrigerants. Compressor performance is also positively influenced, with lower suction and discharge pressures noted. Additionally, nano-refrigerants exhibit shorter on-cycles, indicating quicker cooling velocity and contributing to overall energy savings. Despite these benefits, challenges such as stability and pressure drop in the system underscore areas for future investigation and optimization.

High rates of perishable fruit and vegetable (FV) loss during storage are a serious problem that is addressed in the paper "An IoT-Based Real-Time Intelligent Monitoring and Notification System of Cold Storage" by Hina Afreen and Imran Sarwar Bajwa (2021). Using Internet of Things (IoT) technology, the authors describe a Real-Time Smart Surveillance and Alert System (RT-IMNS) that monitors critical environmental parametersin cold storage, including temperature, relative humidity, luminance, and gas concentration.The system makes use of sensors, Bluetooth and wireless communication technologies, and an artificial neural network (ANN) to enable decision-making. Classifying the quality of stored commodities into three categories—good, unsatisfactory, and alarming—the ANN model obtains a 99% accuracy rate. Through an Android smartphone, the RT-IMNS delivers real-time notifications, enabling staff members to respond promptly and lower FV losses. Interms of forecasting accuracy, the suggested method performs better than current models such as Data Mining (DM), Adaptive Naïve Bayes (ANB), Compress Sending (CS), and Extreme Gradient Boosting (XGBoost). The schematic depiction of the whole RT-IMNS workflow is displayed below in Figure 2.9.

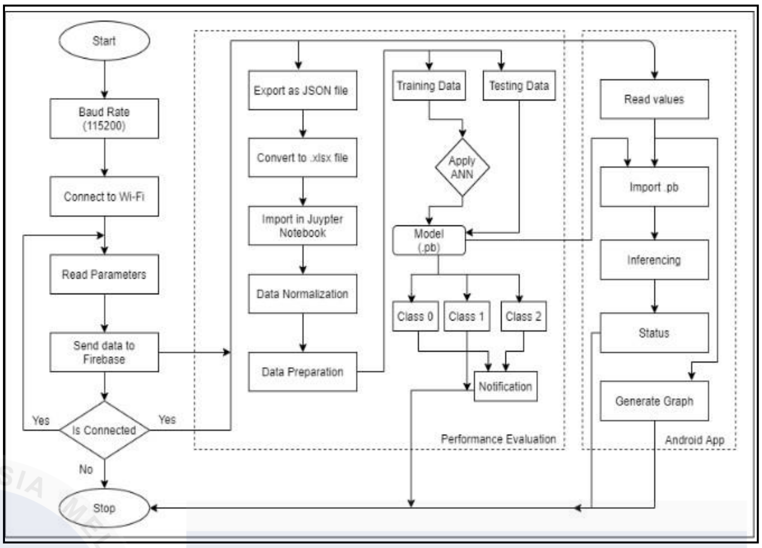


Figure 2.9 Schematic description of complete workflow of RT-IMNS.

(Hina Afreen and Imran Sarwar Bajwa, 2021)

Notable features of the system include real-time monitoring and notification of multiple environmental parameters, high accuracy (99%) using an ANN model with forward propagation, an effective decision support system integrated with an Android application forreal-time alerts, and enhanced precision, recall, and F1-scores for different commodity statusclasses. Despite the advancements presented in the RT-IMNS, several areas remain unexplored or insufficiently addressed. The study focuses on a specific experimental setup involving potatoes, and there is a need for further research on the scalability and adaptabilityof the system to other types of perishable commodities and varying storage conditions. The long-term stability and maintenance of the system, especially the sensors and wireless communication modules, are not thoroughly discussed. Research could explore the durability and maintenance requirements of the system over extended periods.

While the system is described as cost-effective, a detailed cost-benefit analysis consideringinitial setup, maintenance, and operational costs versus the economic benefits of reduced FVlosses could provide deeper insights into its practicality for large-scale adoption. The integration of the RT-IMNS with existing cold supply chain management systems and its impact on the overall efficiency of the supply chain is another area that warrants further investigation. Furthermore, the usability of the system from the perspective of personnel in charge of monitoring and maintaining the cold storage conditions needs more focus. The efficacy of the system might be improved by doing research on interface design and user training.

The paper titled "Advanced Control Strategies for Heating, Ventilation, Cooling systems, and Refrigerator Systems—An Overview: Part I: Hard Control" by Naidu and Rieger (2011)n provides a comprehensive chronological overview of advanced control techniques used to HVAC&R systems. This overview primarily focuses on hard-control approaches such as robust, optimum, nonlinear, adaptive, and proportional-integral-derivative (PID) controllers. The writers make a distinction between "soft" and "hard" control tactics, with Part I concentrating on the former. Conventional mathematical and algorithmic techniques are referred described as "hard" control, but techniques like artificial neural networks, fuzzy logic, and algorithm evolution are considered "soft" control.

The overview focuses on how these hard-control techniques have evolved and been applied to enhance the efficiency, dependability, and performance of HVAC and refrigeration systems. Because of its ease of use and efficiency, PID control is still a fundamental strategy; however, more sophisticated techniques, including optimum control, have been created to satisfy certain performance requirements. While adaptive and robust controls offer mechanisms to handle system uncertainties and variations in operating conditions, nonlinear control techniques address the intrinsic nonlinearities in HVAC&R systems. Hard-control tactics have advanced, yet there are still a number of unanswered questions and difficulties in the field. The expense, complexity, and scalability of integrating these control mechanisms into current HVAC&R systems continue to be major concerns.

The long-term stability and maintenance needs of these cutting-edge control systems in practical applications demand more investigation. Further research is needed to fully understand how various control strategies interact with the system architecture as a whole to maximize performance under varied circumstances. While the article provides valuable insights into the development and application of hard-control techniques, there is a lack of comprehensive studies on the economic impact and practical implementation challenges of these advanced strategies. Future research could benefit from a detailed analysis of the cost- benefit trade-offs, considering the initial investment, maintenance costs, and potential energy savings. Moreover, user training and the usability of these advanced control systems need more focus to ensure effective adoption and operation by HVAC&R personnel.

The article "HVAC Design for Pharmaceutical Facilities" by (Bhatia, 2019) outlines the crucial role that heating, ventilation, and air-conditioning (HVAC) systems play in pharmaceutical manufacturing. In this sector, maintaining specific environmental conditions is vital for product quality and compliance with regulatory standards, particularly those set by the U.S. Food and Drug Administration (FDA) and other global standards like GMP (Good Manufacturing Practices).

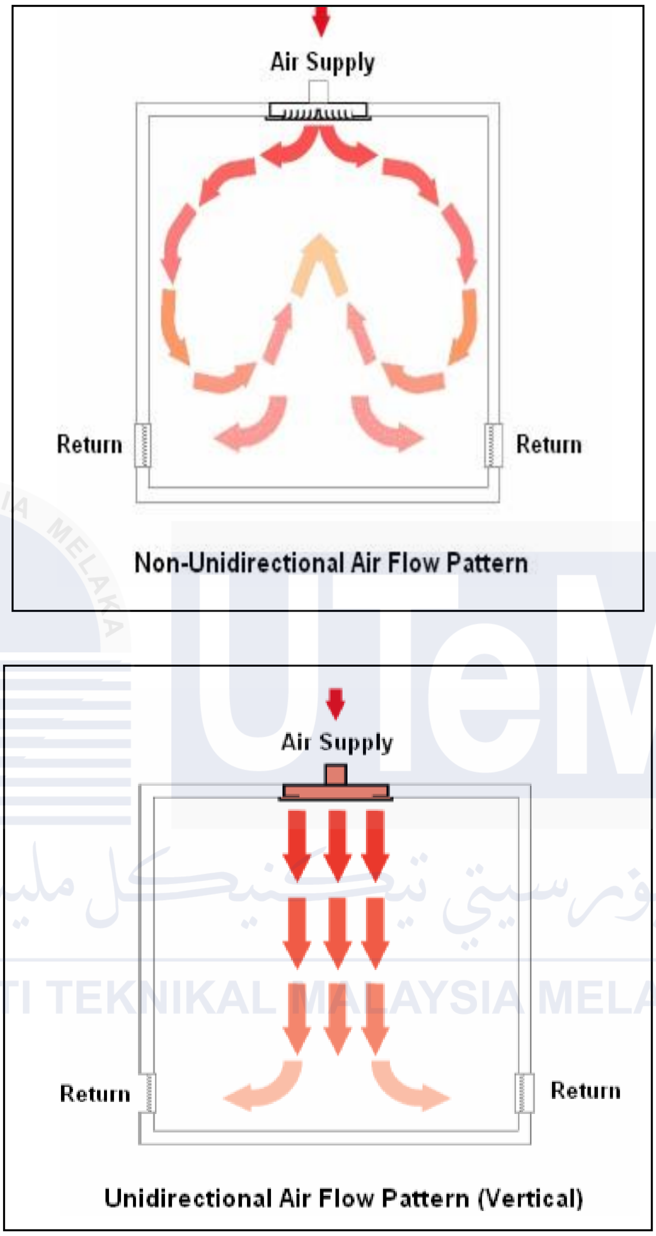


Figure 2.10 Non unidirectional air flow patter and unidirectional air flow pattern vertical by (Bhatia, 2019)

Figure 2.10 shows Unidirectional airflow in cleanrooms involves parallel streams of air flowing in a single direction, maintaining a laminar flow pattern with minimal deviation. This airflow pattern is crucial for maintaining low levels of airborne contaminants, making it suitable for environments where internal contaminants are a primary concern clean air comes from the ceiling then discharged through the base of side walls or an elevated floor in vertical down flow cleanrooms. Similar methods are used by horizontal flow cleanrooms, which have both supply and return wall on opposing sides. The text highlights the strict control of temperature, humidity, particles counts, airflow structure, and pressure variations across rooms when discussing HVAC design considerations for pharmaceutical plants. To dilute pollutants, cleanrooms need a higher air supply—typically 50–100 air changes per hour as opposed to 2–10 in comfortable air-conditioned areas. They also utilize high- efficiency HEPA filters, laminar airflow, and room pressurization to maintain cleanliness. The primary functions of HVAC systems in pharmaceutical facilities include controlling airborne particles through high-efficiency particulate air (HEPA) filters, maintaining room pressure to prevent contamination, regulating humidity to ensure drug stability, and controlling temperature to prevent microbial growth. These parameters are meticulously monitored as they directly impact product quality.

HVAC systems, however, cannot clean surfaces or compensate for human error in following procedures. The pharmaceutical manufacturing process involves several stages: reaction, separation, crystallization, purification, and drying. Each stage has specific requirements for environmental control, and HVAC systems must be designed to meet these needs. The concept of cleanrooms is integral to pharmaceutical manufacturing. Cleanrooms are classified based on the concentration of airborne particles, with classifications varying from Class 100 to 100,000 in the U.S. standards, and Grades A to D in European standards. These classifications dictate the acceptable levels of particulate matter in different manufacturing environments to minimize contamination. Overall, the article emphasizes the importance of a well-designed HVAC system in maintaining cleanliness, controlling and environmental factors

The study by (Liu, 2009) highlights efforts to enhance energy efficiency in pharmaceutical manufacturing while maintaining product quality and occupant comfort. An energy management tool is devised to monitor efficiency and calculate cooling loads, identifying HVAC systems as major energy consumers. Adjustments to AHU operation schedules in office and manufacturing buildings, along with motion detection lighting control, aim to reduce waste. These measures can lead to significant energy savings and cost reductions. Additionally, a spreadsheet tool is developed to optimize dehumidifier settings and temperature control, providing further efficiency enhancements.

A methodical strategy to assess household energy systems (HES) in various climates is presented in this study by (Usman et al., 2022). A total of fourteen combinations of HVAC and energy supply systems are evaluated based on non-renewable energy savings, emissions, expenses, and comfort. The framework of multi-criteria decision-making facilitates the identification of ideal solutions for climates. The findings suggest that absorption chillers are a good choice in hot areas and ground source heat pumps in cold climates. Sensitivity analysis verifies that the decision-making process is robust. By offering a thorough evaluation technique for HES that considers a variety of performance indicators and climate circumstances, the study closes a research gap.

The paper by (Israa Ismael, 2020) compares high voltage direct current (HVDC) transmission with high voltage alternative current (HVAC) technology in integrating renewable energy sources, particularly focusing on photovoltaic systems. HVDC allows for long-distance transportation of renewable power with minimal losses, enabling large-scale solar power integration into the current grid. The study, conducted on the Iraqi Super grid using PSS/E software, evaluates the impact of renewable energy penetration on power load flow and short circuit levels (SCLs) using double circuit links for HVAC and bipolar links for HVDC. Simulation results indicate that HVDC systems outperform HVAC systems in terms of minimizing power losses and SCLs.

The paper "Overview of HVAC system simulation" by (Marija Trčka et al., 2019). This study offers a comprehensive overview of heating, ventilation, and air-conditioning (HVAC) system modeling and simulation. It begins by categorizing tools for HVAC system design and analysis based on the specific problems they are designed to address. These tools range from simple spread-sheet tools to more advanced simulation tools, covering various aspects of building design and performance. The paper then delves into the modeling approaches used for HVAC components, controls, and systems, highlighting the different techniques employed in simulating these aspects. It discusses how models can be continuous or discrete in state and time, as well as deterministic in nature.

Furthermore, the integration of building and HVAC system models is explored, with distinctions made between sequentially coupled models and fully integrated ones. The paper emphasizes the importance of considering system deficiencies when calculating building thermal conditions. Finally, the paper addresses the challenges and considerations in selecting an appropriate HVAC modeling approach, noting that different approaches require varying levels of user skills, resolution, and customization capability. It also highlights the need for further research and development in this area to address the complexities of modernbuildings and HVAC systems. Overall, the paper provides a valuable resource for understanding HVAC system simulation, offering insights into the available tools, modelingapproaches, and simulation techniques.

Table 2.1 Summary of previous research findings

No.	Literature Title	Strength	Weakness	Notable Features	Reference
1.	Cooling Performance Evaluation of Cold Storage System	In-depth investigation of coldstorage's temperature distribution	Limited focus on factors beyond temperature distribution	Experimental measurement andnumerical simulation	Sularno etal., (2018)
2.	Temperature Mapping Study on a Cold Room	Evaluation of temperature distribution in different scenarios	There is little discussion of howoutside variables affect temperature distribution	Monitoring at multiple locations usingdata loggers	Naveen etal., (2017)
3.	Energy-Efficient HVAC Systems	Emphasis on energy efficiency in HVACsystems	Lack of specific focus on experimental data or case studies	Wide range of topics covered inthe Special Issue	Jouhara & Yang (2018)
4.	Membrane Heat Exchangerin	Examining membrane heat	Limited discussion on	Experimental measurements	Nasif et al. (2020)

	HVAC Energy Recovery Systems	exchangers' thermal efficiency and possible for energy savings	practical implementation and real-world applications	and comparison with conventional systems	
5.	Energy Conservation in Room Air Conditioner Unit	An inventive method for reducingenergy consumptionin room air conditioners	Limited discussionon scalability and applicability in different climatic conditions	Utilization of condensate dripsfor cooling	Nethaji etal., (2019)
6.	Sustainability of Heating, Ventilation, and Air-Conditioning (HVAC) Systems	Comprehensive examination of sustainability aspects in HVACsystems	Limited discussionon specific strategies for retrofitting existing HVAC systems	Emphasis onenergy efficiency, indoor air quality, and sustainability	Asim et al., (2022)
7.	Review of Predictive Maintenance Algorithms	thorough analysis ofHVAC systems' PdM algorithms	Limited accuracyand applicability of	Categorization ofPdM algorithms into knowledge-	Es-sakali etal (2020).

	Applied to HVAC Systems		knowledge-based models	based, model-based, and data- driven approaches	
8.	Improving the energy performance of cold stores by J.A. Evans et al. (2020)	-A range of possible energy savings, from 8% to72%, was identified. Improvement payback periods arebrief, frequently less than a year. Thorough auditsconducted in 28 European cold stores.	- small sample sizeof refrigerated stores under audit. -Potential difficulties in putting suggested improvements intopractice are not covered in the study.	-Detailed analysis of energy efficiency issues in cold stores. - Clear quantification ofpotential energysavings.	Evans, J.Aet al., (2021).
9.	The Coefficient of Performance (COP): Refrigeration vs. Heat pump	Provides a comprehensive explanation of the coefficient of performance	Lack of empirical data or case studies to support	Detailed explanation of COP concept, clear differentiation	Mukherjee,N. (2023).

		(COP)concept	theoretical explanations	between coolingand heating COPs	
10.	Cold Room Temperature Mapping Studies	Provides essential evidence for vaccine storage safety	Relatively new concept in low- and middle-income countries	Highlights importance of temperature mapping studies	Unicef.(2020)
11.	Improving Energy Efficiency of HVAC Systems: A Review	Comprehensive overview of energyefficiency	Limited focus on specific case studies	Integrated optimization framework for HVAC systems	Simpeh etal. (2021)
12.	Review Paper on Energy Efficiency Technologies for Heating, Ventilation, and	Comprehensive overview of energyefficiency technologies for HVAC systems	Limited discussio n on specific case studies	-Investigates different technologies andapproaches to improve HVAC system	Bharati (2017)

	Air Conditioning (HVAC)			performance andreduce energy consumption	
13.	Thermodynamic and Energy Efficiency Analysis of a Domestic Refrigerator Using Al2O3 Nano-Refrigerant	- Investigation of nano refrigerants indomestic refrigerators	- Limited stabilityat higher nanoparticle concentrations	- Enhanced thermodynamic performance observed	Sarrafzadeh et al. (2021)
14.	An IoT-Based Real-Time Intelligent Monitoring and Notification System of Cold Storage	- Real-time monitoring of multiple environmental parameters High prediction accuracy (99%)	- Limited focus ononly cold storage applications	- Use of IoT andANN for intelligent monitoring - Comprehensivesystem including Android app	Hina Afreen, I.S.Bajwa (2021)
15.	Advanced control	Comprehensive overview of	Lack of detailed	- Pay attention toconventional	D.

	strategies for heating, ventilation, air-conditioning, and refrigeration systems—An overview: Part I: Hard control	hard-control strategies for HVAC&R systems.	analysis on the economic impactand practical implementation challenges.	control strategiessuch as robust, adaptive, nonlinear, PID, and optimum control.	Subbaram Naidu et al. (2011)
16.	HVAC Design for Pharmaceutical Facilities	Detailed coverageof HVAC design considerations specific to pharmaceutical manufacturing and	May not cover latest advancements in HVAC technology.	-Emphasis on maintaining cleanliness, controlling airborne particles, room	(Bhatia, 2019)
17.	Improving energy efficiency in a pharmaceutical.	- Offers a comprehensive approach to enhancing energy efficiency	- May lack specific details on implementation savings and energy reduction strategies	Develops an energy management toolfor monitoring efficiency and calculating cooling loads	(Liu, 2009)

			-Develops a spreadsheet toolfor optimizing dehumidifier settings and temperature control	-Identifies HVAC systemsas major energy consumers Proposes adjustments to AHU operation schedules and motion detection lighting control -Provides potential cost	
18.	A methodology for multi-criteria assessment of renewable integrated energy supply	Systematic approach for comprehensive assessment. Novel combination of performance	Lack of external funding.	Assessment of household energy systems across different climates using multi-criteria decision-	Usman et al., (2022)

	options	indicators.		making.	
19.	Comparative Study of HVDC and HVAC Systems in Presence of Large Scale	- Enables long-distance transportation ofrenewable powerwith minimal losses.	- Limited focus on specific geographic region(Iraqi Super grid).	- Investigates integration methods of photovoltaic systems with HVDC and	Israa Ismael etal.(2020)
20	Renewable Energy Sources	Demonstrates superiority of HVDC over HVACin minimizing power losses and short circuit levels.		HVAC - Simulation -based study using PSS/E software.	
21.	Overview of HVAC system simulation	Provides an overview of HVACsystem modeling and simulation, categorizing tools	Focuses mainly on HVAC systems, limiting the scope of the	Summarizes current approaches for modeling HVAC components,	Marija Trčka et al.(2019)

		based on their Intended use cases.	overview.	controls, and Systems.	

2.7 Coefficient of Performance (COP) Analysis

2.7.1 Theoretical Basis

The coefficient of performance (COP) is a crucial metric for evaluating the efficiency of refrigeration systems. As the ratio of anticipated output (refrigeration impact) compared to required input (energy expenditure), it provides a quantitative assessmentof how well a system with refrigeration will transfer energy from a cold room to a warm one. COP computations are theoretically based on a branch of thermodynamics known as the Carnot efficiency principle. The highest efficiency an engine with heat working between two temperatures sources may achieve is known as the Carnot efficiency. It establishes maximum theoretical efficiency for each heat engine and refrigeration system.

Formally, the Carnot efficiency (η) is expressed as: $= 1 - \frac{Tcold}{Thot}$

In refrigeration systems, the cool reservoir's temperature is represented by $Tcold$, whereas the hot reservoir's temperature is represented by $Thot$ (typicallythe condenser temperature). The ratio of the anticipated chiller produces (cooling effect) to the energy supplyneeded to operate the system is known as the coefficient of efficiency, or COP, in terms of cooling systems. One can express the COP ($COPref$) numerically.

$$\boxed{COF_{ref} = \frac{Q_{ev}}{W_c}}$$

Here, Qev stands for the energy that the evaporator's liquid absorbs (the cooling effect). The physical electricity supply that the compressor gets is denoted by Wc. The relationship between the necessary energy consumption and the intended cooling effect is determined by a coefficient of performance (COP), which provides important insights into the efficiency of refrigeration systems. The COP is still a crucial metric for assessing and enhancing the performance of refrigeration systems, though.

2.8 Application to Cold Room Systems

When talking about cold room systems, it is important to look at the coefficient of performance (COP), which provides a numerical depiction of the system's ability to cool. Byusing COP analysis on cold room systems, we can evaluate how well these systems maintaintemperature stability within the regulated environment. The coefficient of performance (COP) of a cold room is a measure of how well it maintainstemperature stability. It is computed by multiplying the desired freezer production (coolingeffect) by the electrical power input needed to achieve it. More cooling may be achieved perunit of energy input by a cold room system with a higher coefficient of performance (COP), which improves consistency in temperature and management. A variety of features unique to cold rooms must be considered when calculating the COP. Compressor efficiency is one crucial element. It elevates the temperature and pressure of the refrigerant vapor, which is essential to the refrigeration cycle.

The efficiency of the compressor directly affects the amount of energy required to run the refrigeration cycle and, consequently, the coefficient of performance of the cold room system. Moreover, the properties of the refrigerant used inthe cold room system might influence COP calculations. The overall effectiveness of the system is impacted by the thermodynamic characteristics of the various refrigerants, which differ cooling capacity and possible heat of evaporation. The properties of the chosen refrigerant can have a big influence on the cold room system's efficiency and coefficient of performance. When applied to cold room systems, COP analysis allows for a comprehensive assessment of cooling efficiency and temperature stability. Cold room system designers and operators can achieve higher coefficients of performance and maximize cold room system performance by considering several factors like compressor efficiency and refrigerant characteristics.

2.9 Determination of COP/Efficiency

2.9.1 Methodology

The experimental examination to determine the coefficient of performance (COP) of the cold room system followed a specific technique. The strategy employed a scientificapproach to data collecting and temperature measurement analysis in order to calculate COP and evaluate system efficiency. Throughout the data collection process, temperature readings were taken on the cold and hot sides of the cold chamber. To monitor temperature variations in the cold room, a system of strategically placed sensors was employed. Temperature measurements were collected frequently to record variations in temperature over time. COP was calculated using the Carnot efficiency formula, which considered the collected temperature data. This formula determines the maximum practicable efficiency using the Carnot cycle and relates it to the cold room system's actual performance. The required refrigerated output (cooling effect) was compared to the power supply input to calculate the coefficient of performance (COP) for different operating situations or settings.

2.9.2 Practical Application

The Carnot efficiency formula's practical use allowed for the computation of COP in the experimental arrangement. The computation of the COP values under various operating circumstances involved the entry of temperature data from the cold room sensors. The computed COP values were then shown, providing insight into the energyefficiency and cooling effectiveness of the cold room system. Higher results indicatedgreater effectiveness in maintaining temperature stability within the cold room, whereas lower values suggested potential areas for system performance improvement. Interpreting the COP data required examining the ways in which several factors, suchas compressor performance and refrigerant properties, impacted the cold room system'soverall efficiency. Recommendations for enhancing system design and operation, ultimately improving cooling efficacy and energy efficiency, could be made by knowing these parameters and how they affect COP.

2.10 Comparative Analysis

2.10.1 Benchmarking Against Standards

As part of the comparative analysis, the calculated coefficient of performance (COP) values for cold room systems are compared to industry standards or benchmarks. By comparing the COP values from the research study to established efficiency parameters, the efficacy of the cool room system may be evaluated in respect to industry standards. Analyzing the cold room's performance means figuring out how effectively it follows efficiency guidelines and identifying any times it veers off course. This comparison helps to clarify the system's overall effectiveness and efficiency in maintaining temperature stability.

2.10.2 Insights and Recommendations

Through the examination of COP data, system reliability and operational efficiency can be understood. By examining factors that influence COP values, such as compressor efficiency and refrigerant quality, recommendations can be produced to enhance cooling efficiency and raise COP values. The formulation of proposals may entail suggestions for optimizing cooling efficiency by equipment upgrades, operational modifications, or system design enhancements. It is feasible to optimize the cold room system's performance and achieve greater energy efficiency by talking about potential adjustments or changes based on the results of the COP study.

2.11 Summary

The literature study's first part offers a thorough examination of HVAC systems' cooling efficiency with an emphasis on how cold rooms are used in laboratories. It emphasizes how critical it is to keep exact temperatures, maintain the quality of goods, and use as little electricity as possible in a variety of fields, such as scientific research, food manufacturing, and pharmaceuticals. The importance of comprehensive assessments in addressing the challenges of achieving optimal cooling performance—such as insulation quality, performance of equipment, and external climateconditions—is emphasized throughout the chapter. Chapter 2 offers a thorough examination of HVAC system cooling effectiveness while laying thegroundwork for the subsequent chapters' experimental investigation of cooling rates and time to recover.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Organized planning is required in the implementation of a project. Each step is arranged andlisted systematically to facilitate implementation of the project to obtain the workingprocedures of a project that starts from the production of ideas to the stage of product production or better known as methodology, a study to develop the implementation process must be done first. This includes the explanation of all the methods used to complete the project being carried out. All work procedures listed must be followed to facilitate the progress of the project. This process starts from getting the title of the project up to the production of the project from raw materials. After getting several factors that have been considered, then the selection of some specific equipment and components is made. The project that is to be implemented is based on references and studies on the experiment of cooling rate.

3.2 Method Use

Methodology is a method and technique of designing, collecting, and analyzing data to produce evidence that can support a study. Methodology describes how a problem is studied and why certain methods and techniques are used. The purpose of the methodology is to helpunderstand more broadly about the application of the method by making a description of the research process.

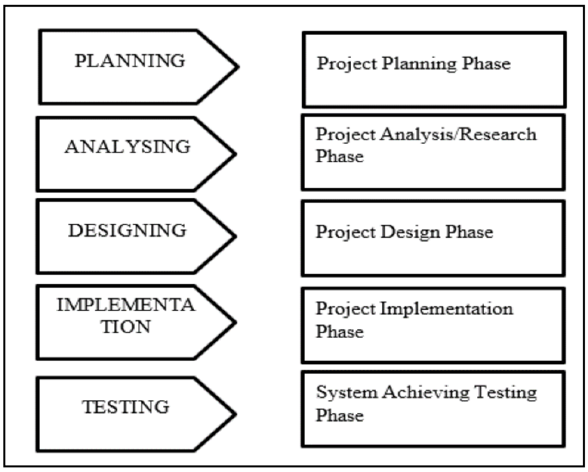


Figure 3.1 Process of preparing this project

In figure 3.1 showing the process of preparing this project, I have listed several steps to ensurethat the project can be carried out without any problems. The steps are as follows:

i. Project planning

Project title: I have discussed with my supervisor and did research on the project title.

ii. Project Analysis

Collecting Data: After choosing the appropriate title, I have obtained information and collected all thedata related to the project that has been selected.

iii. Project Design

Making Project Design: Determining the size of the project, the arrangement and connection of the components used,materials and methods.

iv. Project Implementation

Starting Project Activities: Implement the projects that are specified, namely the Hardware's.

v. Project Testing

Doing Testing: Testing is done to see the functionality of the project.

3.3 Process Flow

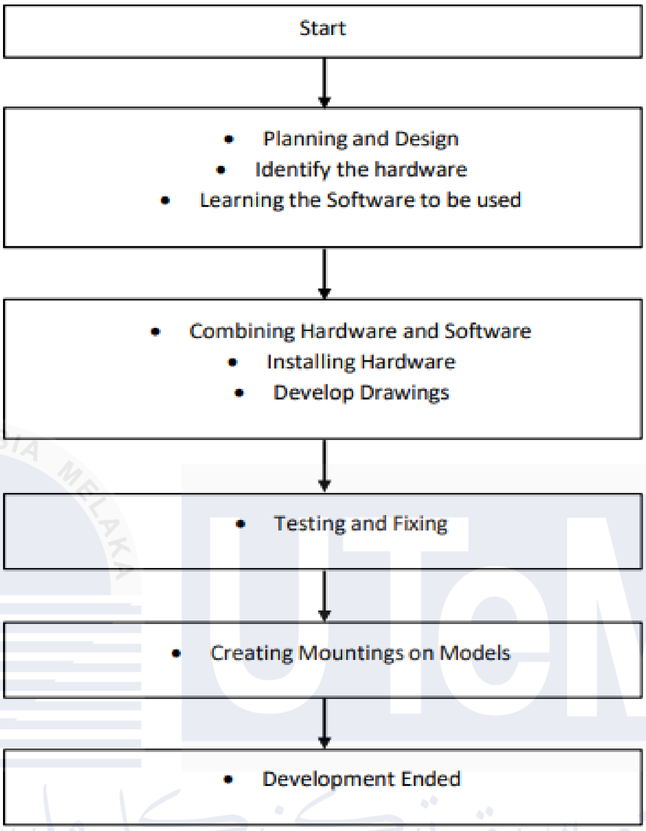


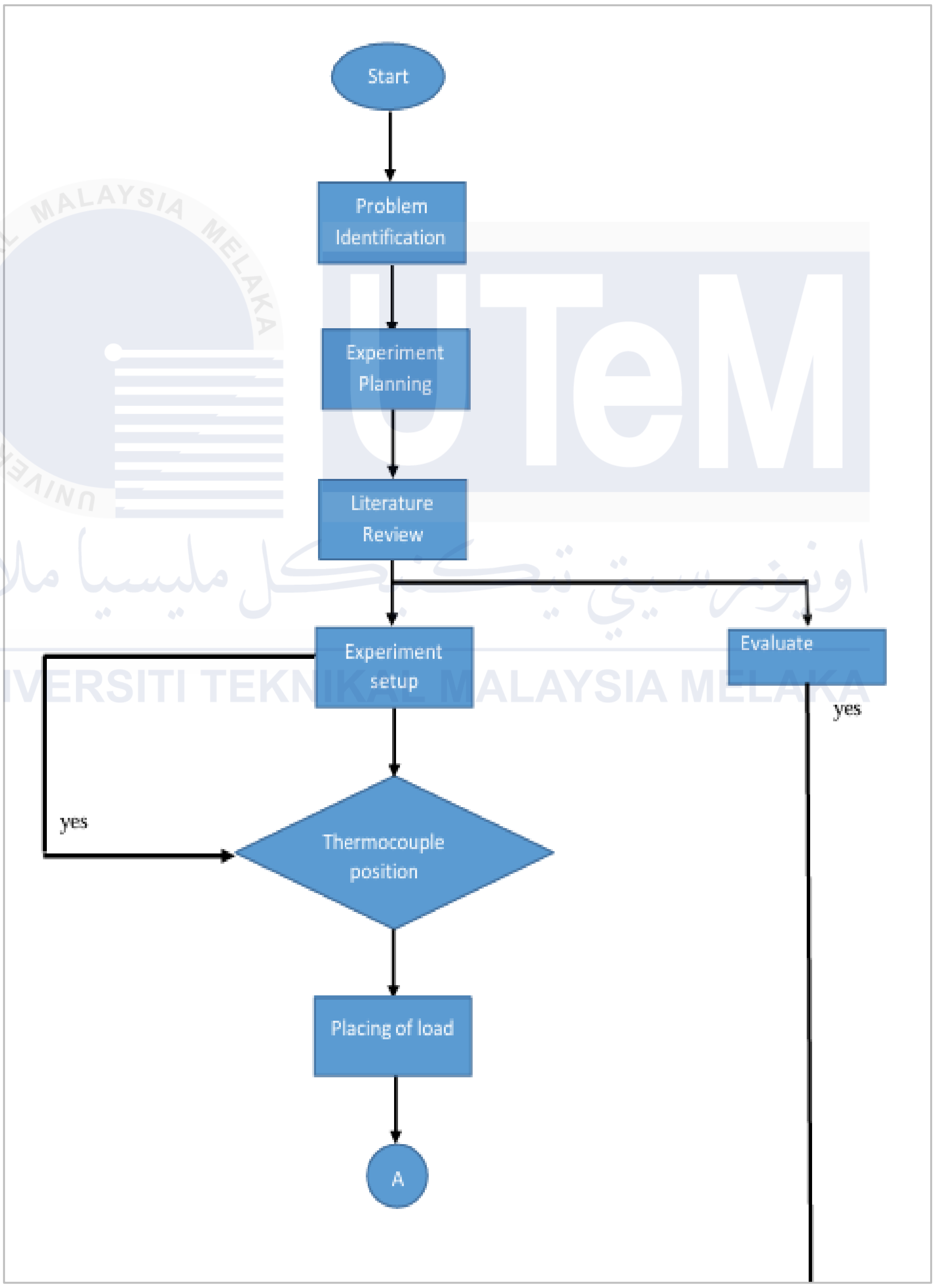
Figure 3.2 Process Flow

Figure 3.2 shows the process flow that must be in place to ensure that the implementation of the project runs smoothly. It can also simplify the manufacturing process so that it is more organized and does not make mistakes when the implementation process is underway.

The process starts with making plans and designs, it can be depicted in a sketch so that it can be done. Next, the hardware and software should be studied so as not to cause any problems when the implementation is being done.

3.4 Proposed Flow Chart

Figure 3.3 shows the flow chart for the experiment that must be in place to ensure the smooth implementation of the research. It can also simplify the process so that it is more organized and can see the movement of my studies.



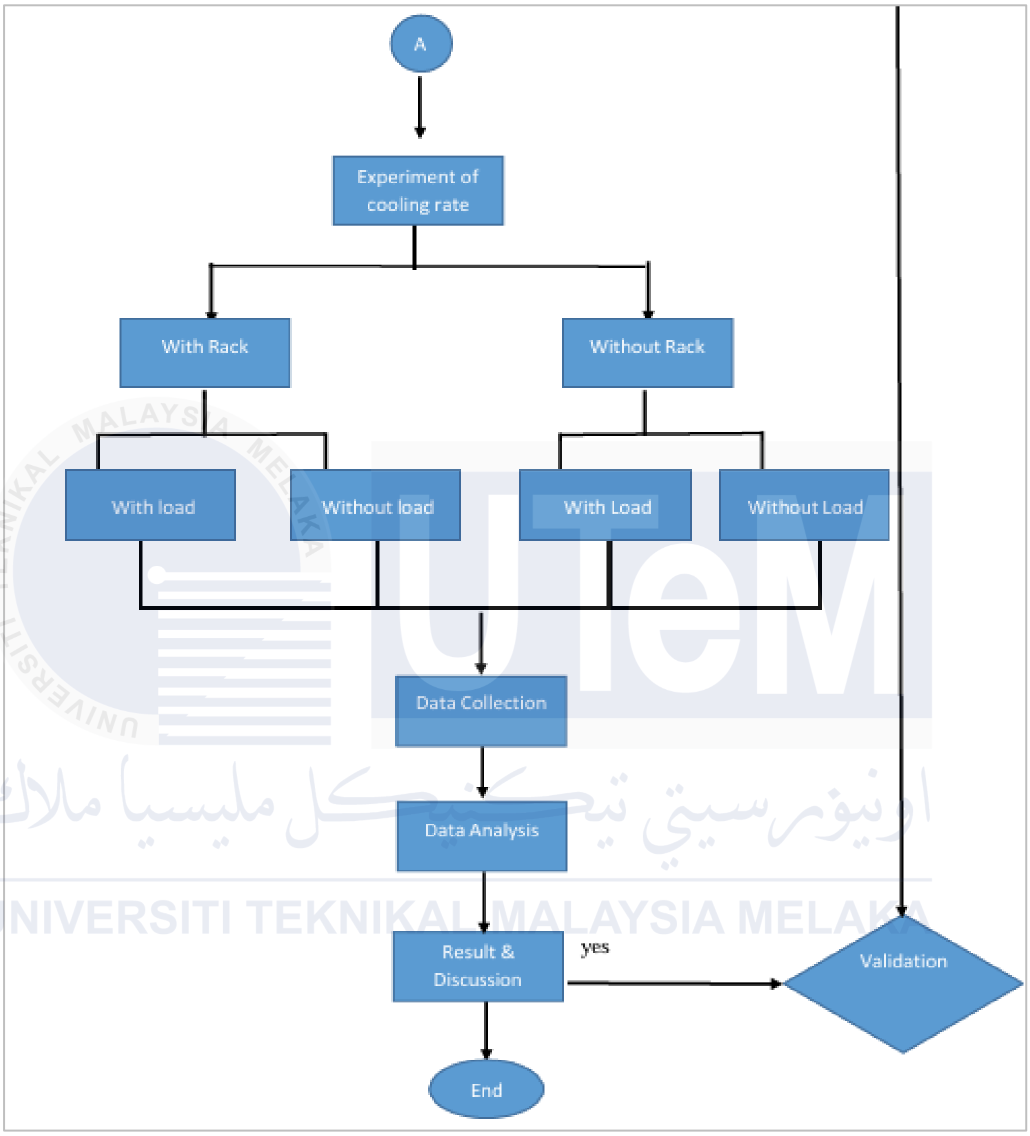


Figure 3.3 The flow chart throughout my experiment

3.4.1 Research Flowchart of condition setting

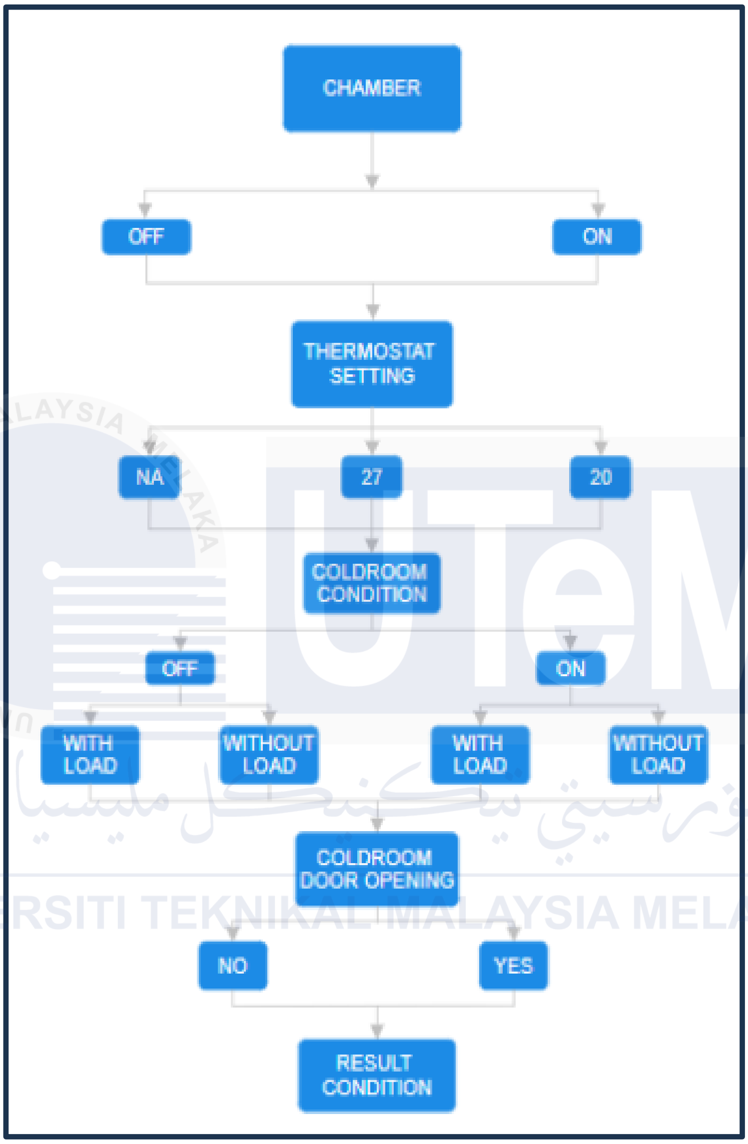


Figure 3.4 Condition setting flowchart

3.5 Hardware Specifications

In the process of doing the experiment for my research, the use and appropriate hardware isvery important to further launch the work process in addition to the safety factor that needs to be emphasized. The equipment and hardware used must be in accordance with the scope of the work being carried out. Here is some of the equipment and hardware. Among the equipment and hardware that will be used for the development of this project are as follows:

Figure 3.5 Centre 309 Data Logger Thermocouple

A simple device called a Centre 309 Data Logger Thermocouple will be used in this experiment to gauge the cold room's temperature at certain locations. As we can see in figure 3.5 Centre 309 Data Loggers is the thermometer that should be utilized; it has fourconnections. A temperature versus time graph that has been recorded for a certain amount of time can be obtained using a thermocouple. The data logger may establish a connection with a computer and use the SE-309 application to capture data.

An evaluation of the temperature distribution and the identification of possible hot or cold patches are made possible by the figure 3.6 HTC-1 Temperature Humidity Meter, which monitors the general temperature in a cold room. To analyses temperature recovery, it additionally monitors the rate of cooling. The performance of the cold room can also be impacted by the humidity level. High humidity can cause the refrigeration unit to work more to cool down and can also lead to frost buildup, which lowers efficiency.

Figure 3.6 Computer setup

Figure 3.7 showing the computer equipped with SE309 software, was an invaluable tool in our temperature monitoring experiment. It automated the data collection process, allowing us to continuously track and record temperature readings from multiple sensors within the chamber. This real-time data was then visually represented on the computer screen, providing insights into the temperature distribution and identifying any potential fluctuations or anomalies. By utilizing this technology, we were able to maintain precise temperature control, ensuring optimal conditions for our experiments.

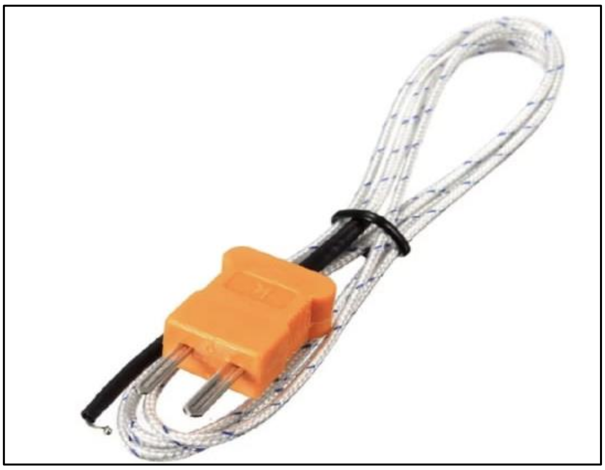


Figure 3.7 K-type thermocouple

To accurately measure the temperature within the chamber, we employed figure 3.7 K-type thermocouples. These sensors are reliable and widely used for temperature measurement applications. By strategically placing these thermocouples at various locations within the chamber, we were able to obtain precise temperature readings. The data collected from these thermocouples was then processed and analyzed using specialized software.

3.6 Research Methodology

This research will be conducted using experimental methods. Which is to determine the cold room's cooling rate experimentally under a range of operating circumstances and outside influences, with the goal of maximizing energy efficiency and performance using a carefullythought-out experimental setup and reliable data collection techniques. To conduct experiments quantifying the impact of door opening frequency on the cooling rate of the coldroom, exploring different opening frequencies effects on temperature stability and energy consumption.

To evaluate, through variable studies, the impact of changing external environmental conditions, such as ambient temperature and humidity, on the cold room's cooling rate and stability while considering elements like equipment specs, ventilation, andinsulation quality.

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3.6.1 Operation description

The figure 3.8 3D drawing of cold storage located at HVAC Application laboratory, FTKM Main Campus features a 220 cm height, 168 cm wide, and 168 cm long cool chamber. A doormeasuring 165 cm in height and 65 cm in width is present. The chamber typically has a thickness of 5 to 10 cm. R-410a, a refrigerant with a mass of 1.8 kg, is the working refrigerantin the vapor compression system used in the cold room. The cold room inside dimensions are 200 cm high by 147 cm wide and 200 cm long. 60 cm wide by 160 cm height is the entryway. There is a PVC strip curtain installed at the entryway. This cold room has a swing door. The cool room's internal volume is 4.3218 m3. It has an 18W lightbulb and an evaporator in the cold chamber. The evaporator's overall dimensions are 54 cm long, 34 cm high and 22 cm wide.

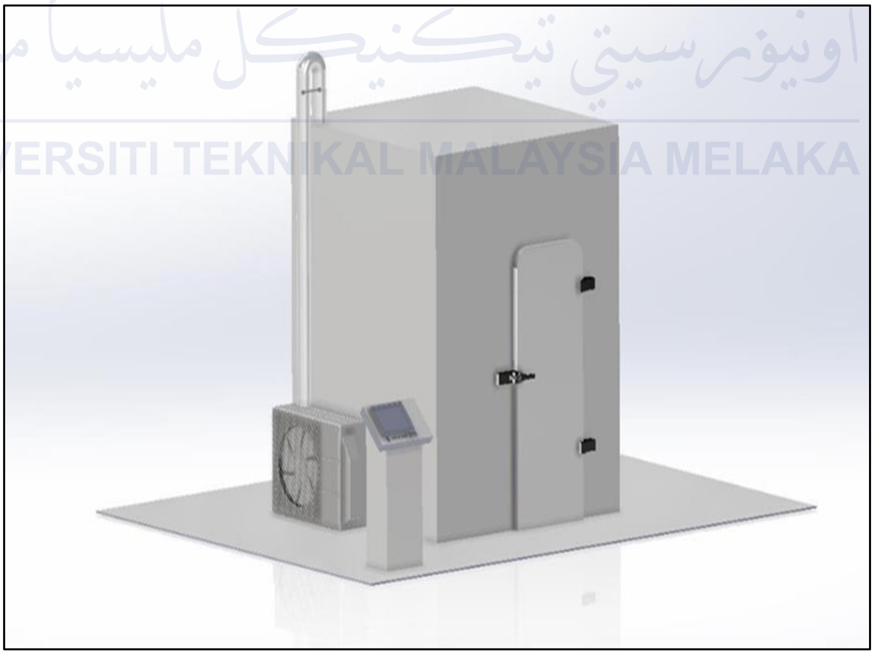


Figure 3.8 3D Drawing of Cold Storage

3.6.2 Experiment Apparatus

For the experiment, a cold room chamber was used as the main apparatus to create and maintain the required low-temperature environment. The system is equipped with a console-type control panel, which serves as the central hub for managing and monitoring the cold room's performance. To ensure efficient operation, the setup includes an inverter power control box, an inverter compressor module, and an inverter drive module, which work together to regulate the refrigeration process. A Data Acquisition (DAQ) PC power system is also included to monitor and collect data during the experiment. Inside the cold room, a lighting lamp switch is available to improve visibility during operation. The chamber is supported by an external refrigeration system, as shown in figure 3.9, ensuring the temperature remains consistent throughout the testing period.

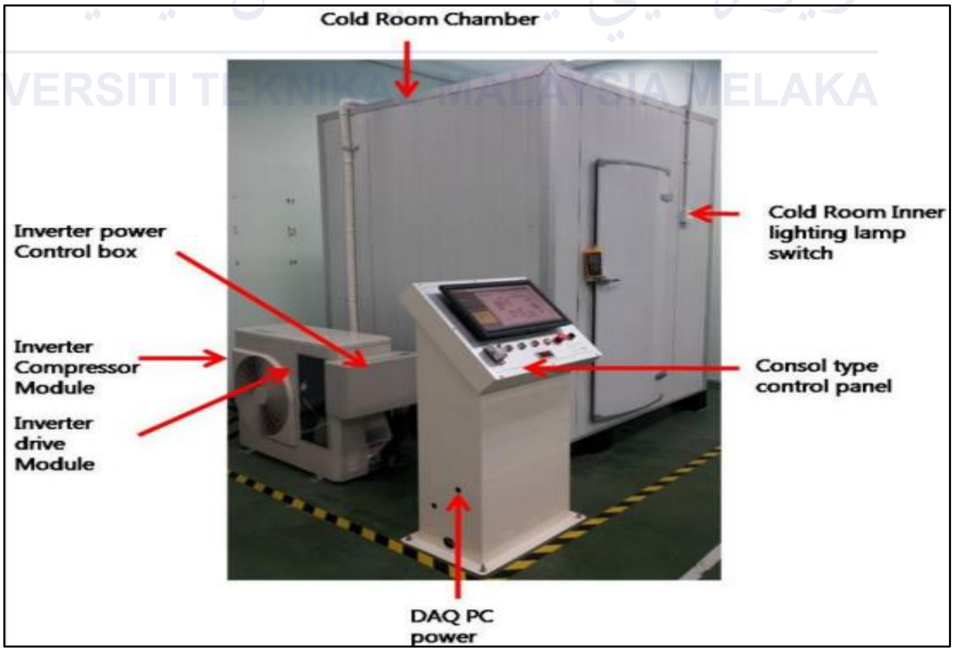


Figure 3.9 Cold Room Layout

The cold room system is equipped with a user-friendly control panel as shown in figure 3.10 that allows for easy monitoring and operation. A monitoring screen displays the system's performance and provides a clear view of the operating conditions, such as temperature and process flow. The panel features several control buttons, including the Fan Start and Fan Stop buttons, which are used to control the fan operation within the cold room. A digital display labeled Room Temp. Shows the current temperature inside the chamber, ensuring accurate monitoring during the experiment. Additionally, a Defrosting switch (s/w) is available to manage the defrosting process when required. For safety and system protection, a Non-Fuse Breaker (NFB) is included on the panel. The combination of these features ensures smooth and efficient operation of the cold room system throughout the experimental process.

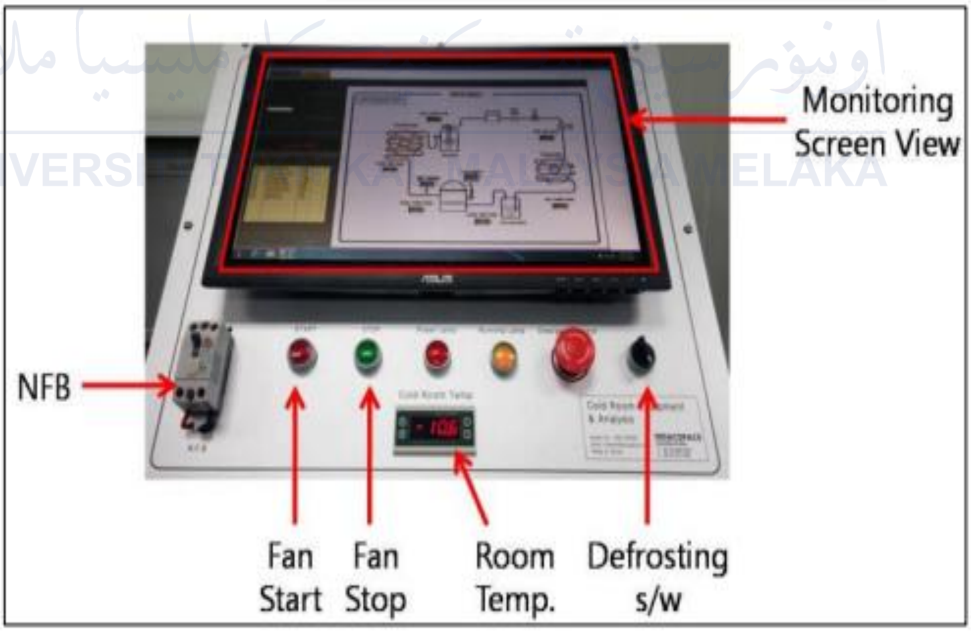


Figure 3.10 Cold Room control pane

3.7 Set up of Experiment

In this section, it shows the equipment and apparatus to set up the experiment and how the experiment is done.

3.7.1 Location of the Experiment

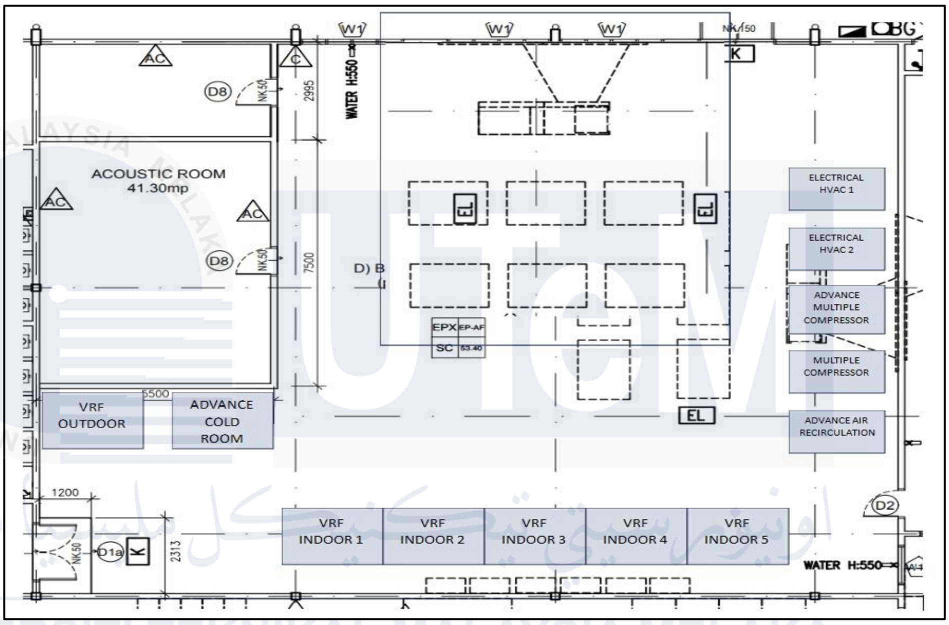


Figure 3.11 Layout of HVAC Application Lab

The test room was in the HVAC Application Laboratory as can see in figure 3.11 on the ground floor of FTKM. Outside of the climate room, the lab had a temperature of roughly 27 degrees Celsius.

3.7.2 Arrangements of Gallon Bottle and Thermocouple Position

Figure 3.12 shows proper drawing using 3D CAD software that the gallons bottles arrangement and racks arrangement are to observe to show the impact of distribution temperature and cooling performance of cold storage. Figure 3.7.2 shows the labeled points "T1" to "T8" represent the locations of temperature sensors within the chamber. These sensors are likely used to measure and record temperature data at different points within the enclosure. Based on the placement of the temperature sensors, the experiment is likely designed to measure temperature distribution by recording temperature data at multiple points, the setup can help understand how temperature varies within the enclosure and to monitor temperature gradients which the sensors can help identify areas of high or low temperature within the enclosure.

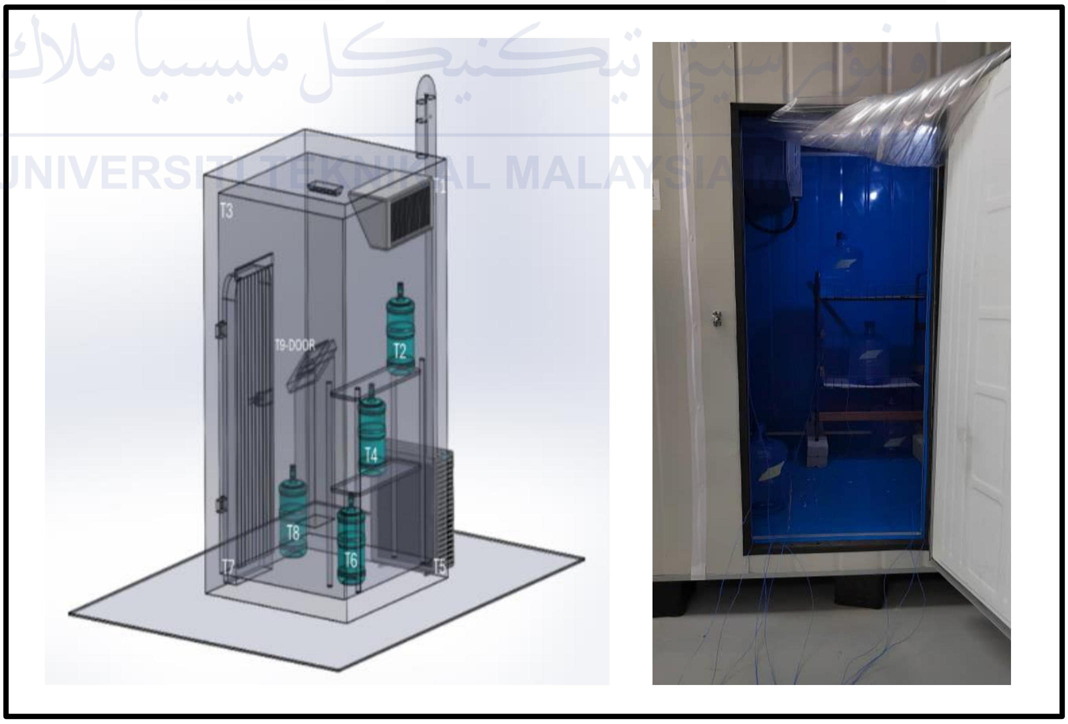


Figure 3.12 Arrangement of Gallons Bottles

3.7.3 Position of Thermocouple in Cold Room

Figure 3.13 shows the labeled points "T1" to "T8" represent the locations of temperature sensors within the chamber. These sensors are likely used to measure and record temperature data at different points within the enclosure. Based on the placement of the temperature sensors, the experiment is likely designed to measure temperature distribution by recording temperature data at multiple points, the setup can help understand how temperature varies within the enclosure and to monitor temperature gradients which the sensors can help identify areas of high or low temperature within the enclosure.

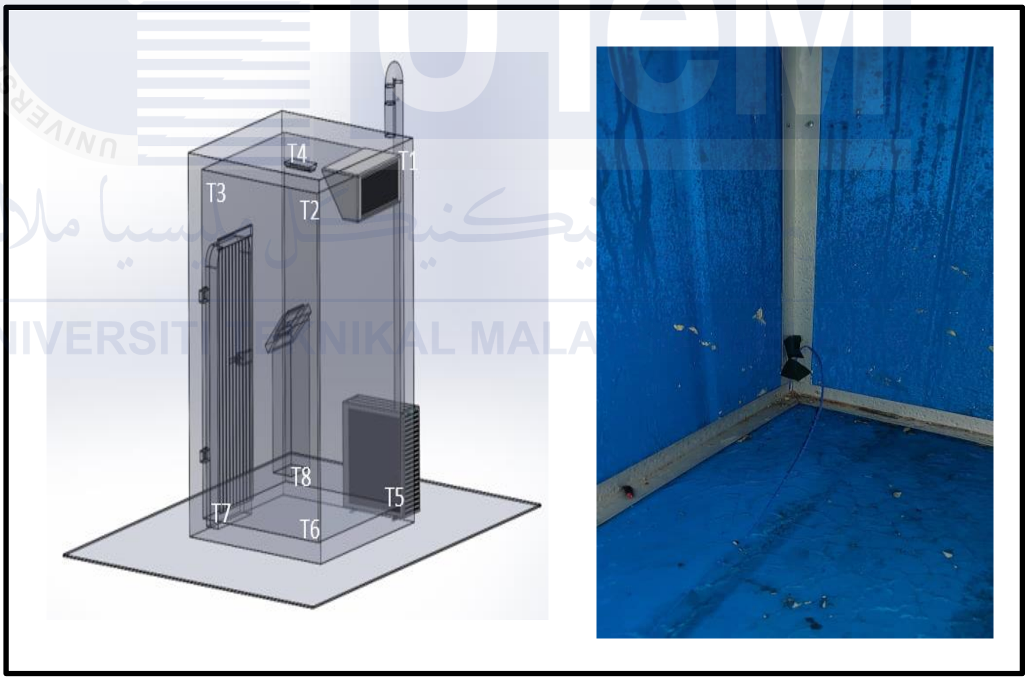


Figure 3.13 Temperature sensor placing in cold room

3.7.4 Chamber Thermocouple Arrangements

Figure 3.14 shows the drawing of thermocouple sensor placed at the HVAC application laboratory. This experiment setup is to observe the temperature of supply and return at the chamber. Points labeled "T1" to "T6" indicate where the temperature sensors are positioned inside the chamber. These sensors are utilized for the purpose of measuring and recording temperature data at various locations. The Cold Room Condenser is the refrigeration system that controls the temperature inside the chamber. Return 1 and Return 2 are the air vents or ducts that bring air back to the cooling unit for recirculation.

Figure 3.14 Temperature mapping on chamber

3.7.5 Chamber Thermostat Setting for Each Condition

To ensure the accuracy and reliability of my experiments, I performed thermostat settings for each chamber involved in the study. The primary reason for this configuration was to determine whether the chambers' internal conditions, particularly temperature had any significant impact on the experimental results.

Each chamber was set to specific temperature parameters using the thermostat control panel, as shown in Figure 3.15. By manually adjusting the thermostat settings, I could establish a controlled environment for each experiment, minimizing external variations that might otherwise interfere with the outcomes. The control panel allowed me to monitor essential parameters, such as temperature and voltage, while ensuring the system operated consistently. This step was crucial because even minor fluctuations in chamber conditions could skew the data and affect the overall integrity of the results. By fine tuning the thermostats, I could isolate the chambers as variables and confirm whether they influenced the experimental process.

Figure 3.15 Chamber Thermostat Setting

3.7.6 Measure Temperature of Cold Room and Chamber

The experimental setup was designed to measure the temperature of the cold room which has each position and chamber, focusing on the return and supply air temperatures. A data logger, as shown in figure 3.16, was employed to capture the temperature variations effectively. Multiple thermocouples were connected to the data logger, with their probes carefully placed at specific locations to monitor both return and supply air temperatures accurately. Ensuring precise placement of these thermocouples was crucial to obtain reliable and consistent temperature data.

The data logger provided the capability to collect simultaneous readings from all connected sensors, making it a practical choice for this experiment. To process and analyze the collected data, SE309 software was utilized. This software served as an interface between the data logger and the computer, allowing for real-time monitoring and visualization of the temperature readings. The recorded data was used to generate detailed graphs, which helped in understanding the temperature behavior within the cold room and chamber.

Figure 3.16 Measuring Temperature Using Data Logger and SE309 Software

3.8 Selection of Thermal Mass Containers (Gallon Bottles Vs 1.5 Liter Bottle)

Table 3.1 Selection of thermal mass

No	**Content**	**Justification**
1	Thermal Mass andHeat Capacity	-Greater Thermal Mass: Gallon bottles have a greater volume and thus a higher thermal mass compared to 1.5-liter bottles. Thismeans they can retain and absorb more heat energy, which can provide a more stable and prolonged thermal load within the cold room. This stability is crucial for accurately measuring thecooling rates and recovery times as it mimics real-world conditions where larger quantities of products are stored. -Improved Heat Transfer Simulation: Larger bottles better simulate the cooling requirements of bulk storage in commercial settings, where large quantities of items are stored together. This allows for a more realistic assessment of the cooling system's performance.

2	Experimental Consistency and Control	-Reduced Variability: Using gallon bottles helps reduce the variability that might occur due to the higher number of 1.5-liter bottles required to match the same total volume. Fewer larger bottles are easier to manage and position consistently within the cold room, ensuring uniform distribution and minimizing variations in experimental conditions. -Consistency in Measurement: With fewer bottles, it’s easier to consistently place temperature sensors and ensure that each bottle is exposed to similar environmental conditions. Thisconsistency is critical for obtaining reliable and repeatable data. -Reduced Variability: Using gallon bottles helps reduce the variability that might occur due to the higher number of 1.5-liter bottles required to match the same total volume. Fewer larger bottles are easier to manage and position consistently within the cold room, ensuring uniform distribution and minimizing variations in experimental conditions.

3	OperationalEfficiency	-Handling and Practicality: Larger bottles are easier to handle interms of filling, sealing, and placing in the cold room compared to a larger number of smaller bottles. This reduces the time andeffort required for experimental setup and can decrease the riskof errors during bottle handling. -Minimized Experimental Errors: With fewer items to manage,the likelihood of experimental errors, such as incorrect bottle placement or misreading measurements due to bottle crowding is reduced.
4	Energy ConsumptionAnalysis	-Realistic Energy Usage: The cooling system's energy consumption and recovery times are more accurately represented when dealing with larger thermal masses. This mimics real-life commercial storage scenarios more closely than smaller bottles, providing more relevant data for energy efficiency analysis. -Load Distribution: Larger bottles can distribute the cooling load more evenly throughout the cold room, allowing for a better assessment of the system's efficiency and the impact of door

		openings.
5	Scientific Validity	-Scaling and Proportionality: Gallon bottles are more representative of typical storage items in commercial cold rooms, such as large containers of liquids or bulk food products. Using gallon bottles ensures that the experimental results can be more directly applied toreal-world situations, increasing the scientific validity and applicability of the findings. -Better Representation of Real-World Conditions: In many commercial cold rooms, products stored are often larger in volume, like gallon bottles, rather than small, individual items like 1.5-liter bottles. This makes the use of gallon bottles a better proxy for real -world conditions, leading to more applicable and actionable insights.

6	Temperature Measurement Precision	-Sensor Placement: Larger bottles provide more surface area and internal volume for placing temperature sensors at various points (e.g., center, edge). This allows for more precise measurement of temperature gradients and a better understanding of the cooling dynamics within the bottle, compared to smaller bottles which may not accommodate multiple sensors as effectively.

In conclusion, table 3.1 shows, the greater thermal mass, better consistency in experimentalconditions, operational efficiency, realistic representation of commercial storage, improvedscientific validity, and better temperature measurement precision of gallon bottles over 1.5-liter bottles justify their use in your experiment. Together, these elements guarantee that theexperimental findings are solid, trustworthy, and appropriate for actual cold storage situations. As a result, they offer important insights into cooling effectiveness and energy usage.

3.9 Parameters

The cold room mapping project aims to ensure that the cold room maintains the desired temperature, identifies hot and cold spots within the chamber, calculates the time required for conditions to return to normal after an excursion, and assesses the impact of power outages or variations in electrical and refrigeration sources. The design of the chamber willinfluence the positioning and quantity of temperature monitoring probes. Therefore, designing the mapping study protocol necessitates a thorough.

3.9.1 Parameters That May Affect the Condition Of The Cold Room.

The cold room chamber must maintain precise temperature settings to ensure its proper functioning. Various factors can impact the condition of the cold room, including external temperature conditions, the frequency of door openings during material handling, power breakdowns, air flow velocity through fans (which should not be less than 2400 CFM), and excessive material stored in the room, which can create a thermal load. Given the potential impact of these parameters on the cold room's performance, it is crucial to subject them to simulated worst-case scenarios during the mapping study.

3.9.2 Loaded Chamber Temperature Mapping / Door Open and Recovery Study.

To verify the room's capability to recover to an acceptable limit after keeping the door open for 10 minutes, a study will be conducted to determine the recovery time. The room will be ensured to be in a loaded condition and switched on, with all sensors operating within the designated limits. The room door will be opened for 10 minutes, and the temperature will be logged every 10 minutes every 1 second using a Centre 309 Data Logger Thermocouple. After the 10- minute period, the door will be closed, and the temperature will be monitored until all sensors reach the acceptance range. The temperature data will be analysed to determine the recovery time.

3.10 Summary

Project planning, project analysis, project design, project implementation, and project testing are some of the steps in the approach employed for this project. You performed research and talked with your supervisor about the project title during the project planning phase. You gathered project-related data during the project analysis phase. During the project design phase, the project's dimensions, the materials, and methods to be employed, and the configuration andconnection of the componentry were all determined. In the project implementation phase, thehardware was implemented, and other project operations were initiated. Lastly, verifying the project's functioning and advancement was part of the testing process.

The project's process flow consists of planning and designing, determining hardware, studying software, integrating hardware and software, installing hardware, preparing drawings, testing, and repairing, mounting components on models, and concluding development. The problem identification, thermocouple position, load placement, experiment planning, literature study, experiment setup, data collection, data analysis, resultand discussion, and validation are all included in the workflow flow chart.

The project's hardware specifications call for the use of an HTC-1 temperature meter to assess temperature distribution and spot potential hot or cold spots, a clamp-on ammeter to measure the cold room's operating voltage and current, a thermocouple to measure the temperature at specific locations, and a Ce

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter focuses on presenting and discussing the results obtained from the experiments conducted to evaluate the performance of the cold room in the HVAC laboratory. The experiments were designed to measure key parameters, such as cooling rates, recovery times, and temperature stability, under various conditions. Using thermocouples strategically placed inside the cold room and the SE309 software, data was collected to monitor how the system responds to different variables, including door opening frequency, load placement, and external environmental factors. These measurements were critical in understanding the system's overall cooling efficiency and energy usage.

The findings from the experiments are analyzed and compared against theoretical principles and previous research to provide a deeper understanding of the cold room's behavior. Graphs and tables generated from the collected data are used to visualize trends and highlight variations in performance under different operating conditions. By critically examining these results, areas of inefficiency are identified, such as longer recovery times or uneven temperature distribution. These insights are vital in pinpointing specific aspects of the cold room system that could benefit from optimization or upgrades.

Through this discussion, the chapter not only sheds light on the system's current performance but also provides practical recommendations for improving its energy efficiency and operational reliability. The analysis presented here serves as a foundation for designing more effective cooling systems and minimizing energy waste, ensuring the cold room can meet the demands of temperature-sensitive environments.

4.2 Maximum Temperature Analysis of Cold Room and Chamber Under Various Load And Operational Conditions

Table 4.1 Maximum temperatures recorded for each condition

	Cold Room				Chamber			Cold Room Thermocouple,(MAX) °C									Chamber Thermocouple, (MAX) °C										
	Cold Room Load	Cold Room Door Opening 10 Minutes	Cold Room Temperature Setting, °C	Cold Room Condition	Chamber Condition	Chamber Thermostat Setting, °C	Time, Hrs	T1	T2	T3	T4	T5	T6	T7	T8	T9	T1(SLY)	T2(SLY)	T3(SLY)	T4(SLY)	T5(SLY)	T6(SLY)	T7	T8	Cold Room Condenser	RETURN 1	RETURN 2
1	Without Load	NO	-15	OFF	ON	27	24										31.2	31.3	31.4	31.3	29.9	29.8			29.1	29.4	29.6
2				ON													31.4	31.2	31.3	31.2	29.9	29.8			29.4	29.6	29.1
3				OFF	OFF	NA											34.3	31.6	31.7	31.5	30.9	31			32.5	30.6	29.2
4				ON													32.2	32.2	32.4	32.4	31.5	31.5			31.4	31.4	34.1
5	Without Load	NO	-15	OFF	ON	20											26.3	25.8	25.8	25.6	24.9	24.8			26.2	26.3	26.4
6				ON													25.7	26.3	26.5	26.1	25.3	25.2			24.4	24.7	28.5
7	Without Load	NO	-15	ON	ON	27		20.5	19	19.2	19.3	15.3	16.8	16.9	17.3										30.3	29.5	30.7
8					OFF	NA		17.8	18.5	18.9	20.5	15.6	16.9	17	16.9										33.8	35	34.8
9					ON	20		18.2	14	15.9	19.3	18	16.2	17.1	19.2										31.1	28.8	28.4
10	With Load	NO	-15	ON	ON	27	24	22.2	14.7	22.4	14.6	19.5	14.7	20.8	14.9	22.8									31.5	29.5	29.1
11					OFF	NA		24.5	18.1	25.4	15.5	21.6	16.7	23.5	16.2	25.2									32.6	31.1	30.7
12					ON	20		25.6	28.4	26.7	28.6	22.7	29.8	25.4	28.8	26.8									33	30.8	30.9
13	With Load	YES	-15	ON	ON	27	8	20.1	24	20.1	24.1	17.3	23.8	17.5	23.9	23.9									31.6	27.8	18.4
14					OFF	NA		23.4	14.6	24.3	14.5	22	14.5	22.3	15.1	22.5									33	30.2	30

Important information about the cold room's performance can be obtained by analysing its distribution, cooling efficiency, and temperature recovery times under various experimental settings. To assess cooling rates, temperature uniformity, and recovery efficiency with and without loads, as well as under conditions such door opening, the experiments were carried out over 14 different settings. The maximum temperature values observed under each scenario are shown in table 4.1 to illustrate key changes and peak thermal performance. Understanding the performance of the chamber conditions was the main goal of the first six conditions, in which there was no load in the cold room.

Understanding the performance of the chamber conditions was the main goal of the first six conditions, in which there was no load in the cold room. Combinations of cold room (ON/OFF) and chamber (ON/OFF) conditions were used in experiments 1 through 6. Condenser returns 1 and 2, as well as thermocouples positioned at six supply points (T1–T6), showed different temperature trends. The supply temperatures were comparatively constant with very slight variations when the chamber was turned on and the cold room was turned off (Conditions 1 and 5). This suggests that the cooling system in the chamber by itself maintained a respectable level of thermal stability. The efficacy of both systems was demonstrated by the notable temperature reduction across the thermocouple sites that occurred when the cold room was turned on in Conditions 2 and 4. The conditions where both the cold room and chamber were OFF (Condition 3) showed elevated and less uniform temperatures, confirming the importance of active cooling systems for maintaining optimal conditions.

To assess temperature homogeneity for Conditions 7 through 9, thermocouples were positioned at eight corners (T1–T8) within the cold room. The findings showed that, with only slight fluctuations, the temperature distribution was generally constant throughout the cold chamber when it was turned on. Condition 7 (cold room ON, chamber ON) produced the most consistent temperature distribution because the two systems worked together to efficiently control cooling across the room. Slight temperature increases at specific corners were noted in Condition 8 (cold room ON, chamber OFF), indicating that the system's capacity to provide consistent cooling was diminished by the lack of chamber cooling. This demonstrates how the chamber helps to stabilize temperature gradients. Condition 9 further validated the system's reliability by reproducing Condition 7 and confirming the cooling performance's reproducibility. The assessment of cooling efficiency with loads was made possible by the addition of gallon bottles in Conditions 10 through 12. The findings showed that the chamber's operational state had an impact on the gallon bottles' rate of cooling. Because of the two systems' complementary effects, the gallon bottles chilled considerably more quickly in Condition 10 (cold room ON, chamber ON). A slower cooling rate was seen in Condition 11 (cold room ON, chamber OFF), highlighting the significance of chamber functioning in preserving low temperatures. The cold room system operates effectively under loaded situations when supported by the chamber, as demonstrated by Condition 12, which replicated Condition 10 and had consistent cooling behavior.

After a 10-minute door opening, the temperature recovery time was assessed in the last experiments (Conditions 13 and 14). The effect of door openings on system performance was demonstrated by the data gathered from the cold room condenser, return 1, and return 2. Because of the combined cooling efforts of both systems, the system demonstrated a shorter recovery time in Condition 13 (cold room ON, chamber ON), with temperatures reverting to baseline levels rather quickly. The slower recovery rate in Condition 14 (cold room ON, chamber OFF), on the other hand, highlighted the decreased cooling efficiency when the chamber system was not in use. The temperature swings seen in returns 1 and 2 throughout the recovery phase serve as more evidence of the difficulties in preserving cooling stability after outside disturbances like door openers.

The results of the experiments show that better cooling performance, temperature homogeneity, and recovery efficiency are achieved when the cold room and chamber systems are operated together. Longer recovery periods, more temperature fluctuations, and slower cooling rates were the outcomes of the chamber system's absence. Additionally, the addition of loads and door openings offered useful information about how the system would function in actual situations, emphasizing how crucial it is to maintain both systems for maximum cooling effectiveness. Based on these findings, operational solutions are suggested to increase thermal stability and energy efficiency in cold room settings.

4.3 Minimum Temperature Analysis of Cold Room and Chamber Under Different Load And Operational Conditions

Table 4.2 Minimum temperatures recorded for each condition

	Cold Room				Chamber			Cold Room Thermocouple,(MIN) °C									Chamber Thermocouple, (MIN) °C										
	Cold Room Load	Cold Room Door Opening 10 Minutes	Cold Room Temperature Setting, °C	Cold Room Condition	Chamber Condition	Chamber Thermostat Setting, °C	Time, Hrs	T1	T2	T3	T4	T5	T6	T7	T8	T9	T1(SLY)	T2(SLY)	T3(SLY)	T4(SLY)	T5(SLY)	T6(SLY)	T7	T8	Cold Room Condenser	RETURN 1	RETURN 2
1	Without Load	NO	-15	OFF	ON	27	24										25.3	16.2	15.9	16.1	27.5	27.4			25.8	25.8	25.7
2				ON													28.2	28	28.1	28	27.9	27.8			26.9	26.9	28
3				OFF	OFF	NA											27.9	28.3	28.2	28.2	27.8	27.7			28.1	27.9	28.1
4				ON													28.9	28.9	29.1	29	28.5	28.5			28.6	28.4	28.6
5	Without Load	NO	-15	OFF	ON	20											19.2	10.7	10.3	10.4	12	11.6			20.1	19.8	19.8
6				ON													19.8	10.6	10.2	10.4	22.7	22.6			20.4	19.8	23
7	Without Load	NO	-15	ON	ON	27		16.8	15.9	15.2	16.6	9.9	11.4	11.5	12.1										25.6	25.4	25.5
8					OFF	NA		5.9	4.7	4.7	7.9	-1	4.5	4.5	6.3										26.3	28.1	28.3
9					ON	20		0.2	-1.7	-0.9	1.1	-0.9	-1.4	-1.2	1										24.7	21.6	21.9
10	With Load	NO	-15	ON	ON	27	24	12.3	12	11.8	11.2	11.6	11.7	11.8	11.8	10.4									24.7	21.1	21.3
11					OFF	NA		14	14.6	13.6	14.6	12.5	14.4	13.8	14.6	14.2									26.8	28.2	28.4
12					ON	20		8.6	9.2	8.1	9.6	7.4	9.5	8.3	9.5	8.3									23	18.7	19.5
13	With Load	YES	-15	ON	ON	27	8	5.1	8.7	2.2	8.7	1.9	8	2.4	8.2	2.6									25.7	26.3	25.7
14					OFF	NA		8.5	10.8	5.6	10.5	5.1	10.4	6.3	10.5	6.2									26.7	26.9	27

Essential details about the cold room's performance can be obtained by analysing its distribution, temperature recovery durations, and cooling efficiency under various experimental settings. To assess cooling rates, temperature uniformity, and recovery efficiency with and without loads, as well as under conditions such door opening, the experiments were carried out over 14 different settings. A clear picture of the system's capacity to reach and sustain low temperatures is given by the data in table 4.2, which shows the lowest temperature values observed under each situation.

Understanding the cooling performance of the chamber and cold room systems separately and together was the main goal of the first six conditions, in which there was no load in the cold room. The lowest recorded temperatures at the supply points (T1-T6) were comparatively constant when the chamber was ON and the cold room was OFF (Condition 1), but they were nevertheless higher than those noted when both systems were in operation. The temperatures at all measured sites were considerably lowered when the cold room and chamber were turned on simultaneously in Condition 2, demonstrating the increased cooling effectiveness of using both systems in tandem. As anticipated given the lack of active cooling, the supply temperatures in Condition 3, when the chamber and cold room were both turned off, remained high. Condition 6, where both systems operated, recorded the lowest minimum temperatures, reaffirming the importance of combined cooling for optimal performance.

Thermocouples were positioned at eight corners (T1-T8) within the cold room for Conditions 7 through 9 to measure temperature homogeneity. Although there were some variances across the corners, especially in locations further away from the cooling sources, the results showed that the cold room system alone (Condition 8) could attain low temperatures. The minimum temperatures were more constant and uniformly lower in Condition 7, when the chamber and cold room were both turned on, suggesting that the chamber system helps to stabilize temperature gradients. Similar low temperatures were attained throughout Condition 9, confirming the performance's repeatability. These results highlight how the integrated system can keep the cold room consistently cooled, guaranteeing that there are no notable hotspots or warm zones remain.

An assessment of cooling performance under loaded situations was made possible by the addition of gallon bottles in situations 10 through 12. The system successfully reached low minimum temperatures in Condition 10 (cold room ON, chamber ON), proving its ability to adequately cool the load. The minimum temperatures increased noticeably in Condition 11, when the chamber was off, suggesting that the lack of chamber support was causing the cooling rates to decrease more slowly. This reaffirms the chamber's function in improving the cold room's capacity to effectively cool large objects. Because the lowest temperatures stayed low and steady, Condition 12, which was a replication of Condition 10, validated the system's reliable operation. The significance of chamber operation in attaining ideal cooling for loaded settings is demonstrated by these tests.

Following a 10-minute door opening, the system's recovery capability was assessed in the last set of trials (Conditions 13 and 14). The system's capacity to recover and stabilize temperatures following a disruption was demonstrated by the lowest temperature readings recorded at the cold room condenser, return 1, and return 2. The efficacy of the integrated system in reacting to disturbances was demonstrated by Condition 13 (cold room ON, chamber ON), where the minimum temperatures reverted to stable, low values faster. A delayed recovery was shown by Condition 14 (cold room ON, chamber OFF), which had greater lowest values throughout the stabilization phase. This delayed reaction underlines the chamber's function in accelerating temperature recovery and draws attention to the shortcomings of the cold room system functioning on its own.

Overall, the minimum temperature readings that were noted under all circumstances offer important information on how well the cool room and chamber systems are operating. The outcomes unequivocally show that, especially under loaded conditions and during recovery times, the combined functioning of both systems produces the lowest and most consistent temperatures. Low temperatures can be reached by the cold room system alone, but the chamber greatly increases its efficiency. These results highlight how crucial it is to integrate both systems for the best cooling, temperature stability, and recovery effectiveness. Recommendations for enhancing energy efficiency, operational tactics, and general performance in cold room settings can be made by comprehending these linkages.

4.4 Temperature Range Analysis of Cold Room And Chamber Under Various Load And Operational Conditions

Table 4.3 Range value recorded for each condition

	Cold Room				Chamber			Cold Room Thermocouple,(RANGE) °C									Chamber Thermocouple, (RANGE) °C										
	Cold Room Load	Cold Room Door Opening 10 Minutes	Cold Room Temperature Setting, °C	Cold Room Condition	Chamber Condition	Chamber Thermostat Setting, °C	Time, Hrs	T1	T2	T3	T4	T5	T6	T7	T8	T9	T1(SLY)	T2(SLY)	T3(SLY)	T4(SLY)	T5(SLY)	T6(SLY)	T7	T8	Cold Room Condenser	RETURN 1	RETURN 2
1	Without Load	NO	-15	OFF	ON	27	24										5.9	15.1	15.5	15.2	2.4	2.4			3.6	3.9	3.3
2				ON													3.2	3.2	3.2	3.2	2	2			2	2.9	4.8
3				OFF	OFF	NA											6.4	3.3	3.5	3.3	3.1	3.3			4.4	2.7	1.1
4				ON													3.3	3.3	3.3	3.4	3	3			2.8	3	5.5
5	Without Load	NO	-15	OFF	ON	20											7.1	15.1	15.5	15.2	12.9	13.2			6.1	6.5	6.6
6				ON													5.9	15.7	16.3	15.7	2.6	2.6			4	4.9	5.5
7	Without Load	NO	-15	ON	ON	27		3.7	3.1	4	2.7	5.4	5.4	5.4	5.2										4.7	4.1	5.2
8					OFF	NA		11.9	13.8	14.2	12.6	16.6	12.4	12.5	10.6										7.5	6.9	6.5
9					ON	20		18	15.7	16.8	18.2	18.9	17.6	18.3	19.2										6.4	7.2	6.5
10	With Load	NO	-15	ON	ON	27	24	9.9	2.7	10.6	3.4	7.9	3	9	3.1	12.4									6.8	8.4	7.8
11					OFF	NA		10.5	3.5	11.8	0.9	9.1	2.3	9.7	1.6	11									5.8	2.9	2.3
12					ON	20		17	19.2	18.6	19	15.3	20.3	17.1	19.3	18.5									10	12.1	11.4
13	With Load	YES	-15	ON	ON	27	8	15	15.3	17.9	15.4	15.4	15.8	15.1	15.7	18.4									15.7	5.9	2.1
14					OFF	NA		14.9	3.8	18.7	4	16.9	4.1	16	4.6	16.3									6.3	3.3	3

Important information about the cold room's performance can be obtained by analysing its distribution, temperature recovery durations, and cooling efficiency under various experimental settings. To assess cooling rates, temperature uniformity, and recovery efficiency with and without loads, as well as under conditions such door opening, the experiments were carried out over 14 different settings. A thorough grasp of temperature stability, variation, and the system's capacity to maintain consistent cooling is provided by the data in the table 4.3, which shows the range of temperature values collected under each condition.

The temperature range in the first six situations, when there was no demand on the cold room, demonstrates the reliability and consistency of cooling in different setups. The temperature range at the chamber supply points (T1-T6) and returns stayed comparatively modest under Condition 1, where the chamber was ON, and the cold room was OFF. This suggests that the chamber system by itself maintained a moderate level of cooling consistency.

The range of temperatures, however, dramatically shrank when the cold room (Condition 2) was turned on, demonstrating enhanced stability and increased cooling effectiveness with both systems operating. As anticipated, because there was no active cooling in Condition 3, where both systems were off, the temperature variations were noticeably wider.

As anticipated, because there was no active cooling in Condition 3, where both systems were off, the temperature variations were noticeably wider. This emphasizes how important it is to have at least one working system to maintain temperature control. The significance of the cold room system was further illustrated by Conditions 4, 5, and 6, since its activation decreased temperature ranges, especially when both systems were running concurrently (Condition 6), which produced the least variance and the steadiest cooling.

Thermocouples positioned at eight corners (T1-T8) within the cold room recorded the temperature change throughout the area for Conditions 7 through 9. The temperature variation in every area was negligible in Condition 7 (cold room ON, chamber ON), suggesting steady and even cooling while both systems were operating. Variations were seen in locations further away from the cooling source in Condition 8 (cold room ON, chamber OFF), which had somewhat wider temperature ranges. This suggests that although the cold room system by itself can supply adequate cooling, the chamber system improves its capacity to maintain homogeneity. The reliability of the system was further validated by Condition 9, which reproduced Condition 7 and verified the reproducibility of steady and uniform temperature ranges.

The performance of the cooling system under real-world circumstances was assessed by introducing gallon bottles into the cold room in Conditions 10 to 12 to replicate a loaded environment. The temperature ranges were smaller in Condition 10 (cold room ON, chamber ON), demonstrating the system's capacity to stabilize and efficiently cool the load.

The temperature ranges expanded in Condition 11 (cold room ON, chamber OFF), suggesting that the cooling process was less consistent in the absence of the chamber system's assistance. This implies that under loaded situations, the chamber is essential for minimizing fluctuations and improving overall efficiency. The ability of the system to reliably handle the load was confirmed by Condition 12, which reproduced Condition 10 and yielded comparable results with small temperature variations. These findings underscore the importance of combined system operation in ensuring efficient and uniform cooling, particularly when the cold room is under load.

After a 10-minute door opening, the temperature recovery process was investigated in the last trials (Conditions 13 and 14). The system's reaction to outside disturbances is demonstrated by the temperature variations seen at the cold room condenser, return 1, and return 2 during recovery. The temperature variations were less in Condition 13 (cold room ON, chamber ON), demonstrating the system's capacity for rapid recovery and efficient temperature stabilization. The slower and less steady response when the chamber system was not in use was highlighted by Condition 14 (cold room ON, chamber OFF), which displayed broader variations during the recovery phase.

This demonstrates the benefit of the integrated system in avoiding temperature fluctuations and rapidly restoring consistent and stable conditions following a disturbance.

All things considered, the temperature ranges that were recorded under all circumstances offer important information on the dependability and stability of the cold room and chamber systems. The findings show that when both systems are operating together, temperature fluctuations are reduced, resulting in more consistent and reliable cooling. Temperature ranges rise while the chamber system is not in use, especially when it is loaded and during recovery times, which indicates decreased stability and efficiency. These results highlight how crucial it is to integrate both systems for best results, particularly in practical situations where rapid recovery and consistent temperature management are essential. It is evident from examining the temperature ranges that both systems work in tandem to provide reliable cooling, enhance energy efficiency, and preserve thermal stability in the cold room setting.

4.5 Result and Analysis

Results analysis involves data analysis and interpretation of the same in relation to the experiment or study conducted. This is the stage where, considering the research questions or hypotheses, the researcher tries to make sense of the results. It includes comparison of observed data with what was expected, observing patterns, correlations, or unexpected findings, and statistical or practical significance determination. Researchers generally use different statistical tests or qualitative analysis to verify the accuracy, reliability, and validity of data. (Dibekulu, 2020)

Result analysis is done to deduce meaningful conclusions that may substantiate or nullify the hypothesis or assumptions made at the beginning. It also involves placing the findings within the wider context of existing research, theories, or frameworks. Result analysis ensures that the trends or discrepancies are isolated, henceforth developing insights to help in the general understanding of the research topic at hand. Also, this sometimes culminates in recommendations for further studies, possible ways of improving methods applied, or how results found can be applied practically in real life (Ferreira, 2020).

4.5.1 Measure Chamber Temperature with Conditions

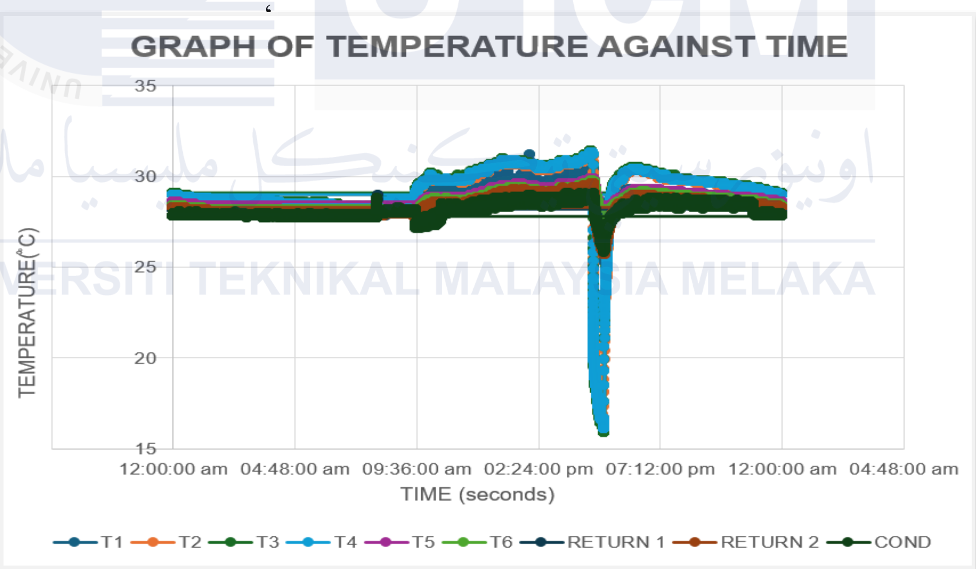


Figure 4.1 Condition 1- cold room off / chamber on

The figure 4.1 for the first condition, where the cold room is OFF and the chamber is ON with the thermostat set to 27°C, demonstrates specific temperature behaviors across all measured points: From T1 to T6 (supply points), and return 1 and 2, and the cold room condenser. At first, temperature changes were small, and temperatures ranged between low of 27°C and high of 29 °C. Such coefficient stability demonstrates that the chamber HVAC is working to hold the desired temperature though regulated by small fluctuations which are common features of HVAC systems like thermal inertia, flow rates and heat exchange.

At approximately 2:24 PM a sharp decline of temperature difference at all the observed points was noted. The temperatures of T1–T6 decrease and sit at the lower range of 22–23°C, and the Return 1&2 temperatures drop to about 20°C. The Cold Room Condenser records the steepest drop-off to as low as 18°C, they reflect and, therefore, cooled it to a greater extent in comparison with other places. This sharp decline is attributable to a temporary activation or perhaps an overcompensation by the chamber's HVAC for detected fluctuation or imbalance in temperature (Service & Service, 2023) .Although the cold room was switched OFF, the chamber cooling system presumably started a cooling cycle, and the chatter propagated to the supply and return points at a fast rate due to the condenser cooling.

After this temperature drop, the readings start a slow, steady climb back up again, as though the running process needs to go through a certain minimum number of cycles before it can maintain optimum temperatures. By approximately 7: All measured points return to its baseline readings of 27°C to 29°C 12 PM as we reconstructed the chamber system and resumed normal operation. This recovery phase underscores the capacity of the chamber HVAC to hold thermal conditions steady even after temporary disturbances (US EPA, 2014) .The much steeper declines observed in the condenser temperature similarly reestablish it as the primary cooling element during this period in H —F.

Therefore, even though the approach of the chamber HVAC system of keeping the temperature adjacent to the thermostat of 27 °C was effective, it was evident that there was a fluctuation and slight overcompensation of the ambient temperature. Cold Room Condenser: A further sharper drops to 18 °C from other recorded points suggests transient response which could have been influenced by thermostat, air flow distribution, or short term improvement in cooling capacity for stabilization. This behavior is also of importance while looking at the total performance of the chamber cooling mechanism under this state of affairs (Zhu et al., 2017).

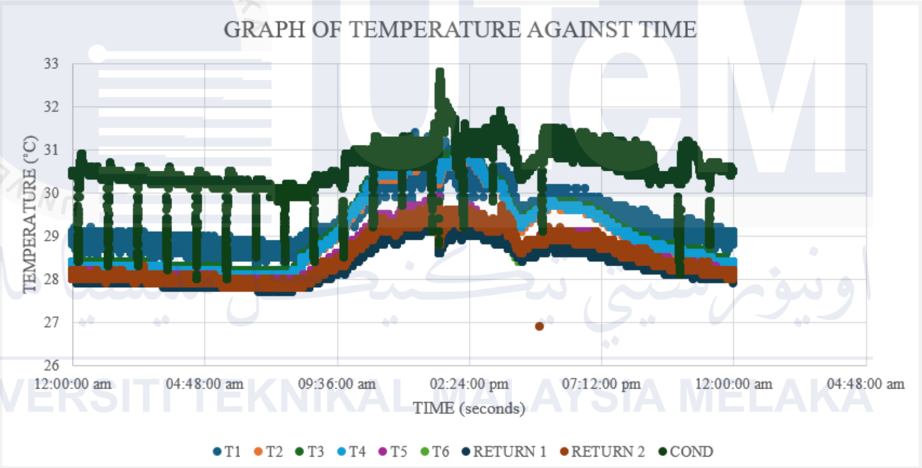


Figure 4.2 Condition 2- cold room on / chamber on

This figure 4.2 shows the fluctuation of temperature in the second experimental condition in which both the cold room and the chamber are run. During the initial hours, from 12: From 00 AM to 9:36 AM, the temperatures at the supply points (T1-T6) are stable for a short range of between 28°C and 29°C. This has further a positive implication in that it shows steady cooling of all the articles and equal distribution of temperature in the cold room. The RETURN 1 and RETURN 2 are slightly higher, 29 ºC as it expected that the air gets heated up as it takes heat before it gets to the cooling unit. During this period, the condenser temperature (COND) is kept constant and is approximately about 30°C which shows that the heat rejection is good in the system.

As the day progresses, particularly between 9:36 AM and 2:24 PM there is a rise in the temperatures by a difference of the given ratio. The condenser temperature operates around 31°C and the supply temperatures T1 to T6 slightly rise, suggesting that the system is taxed more on heat load. This behavior is observed especially in the morning or in the afternoon when the atmospheric temperature is high, or a lot of heat invades the chamber. The intermittent spikes in the supply temperature are believed to be an effect of several short duration compressor cycles to control the more efficient temperature range (Engler & Krarti, 2021).

By 7:12 PM is when stabilizing starts for the same reason as mentioned earlier the external heat load reduces in the evening and at night. The supply and return temperatures return to the optimum flow range of between 28°C and 29°C and the condenser regains its stable temperature of just over 30°C. It proves that the system can adequately cool the building, keeping the environment cool during the day if there are fluctuations in heat loads throughout the day. The variations in the supply temperatures shown in this figure are typical for the system operation and described the nature of the refrigeration cycle.

In conclusion, the graph shows that the cold room and chamber operate efficiently under this experimental condition, maintaining consistent temperatures despite fluctuations in heat load. The system's performance, characterized by stable supply and return air temperatures and effective heat rejection by the condenser, highlights its capability to sustain optimal cooling conditions. These results validate the system's reliability and suitability for the intended application in this setup. As conclusion, the graph identifies that both the cold room and chamber maintain reliable performance under this experimental condition, which is irrespective of heat load. Stable supply and return air temperatures as well as efficient heat rejection by the condenser provide evidence of the system ability to maintain favorable cooling conditions. These results support the argument that the system is accurate and appropriate for the designed purpose in this configuration.

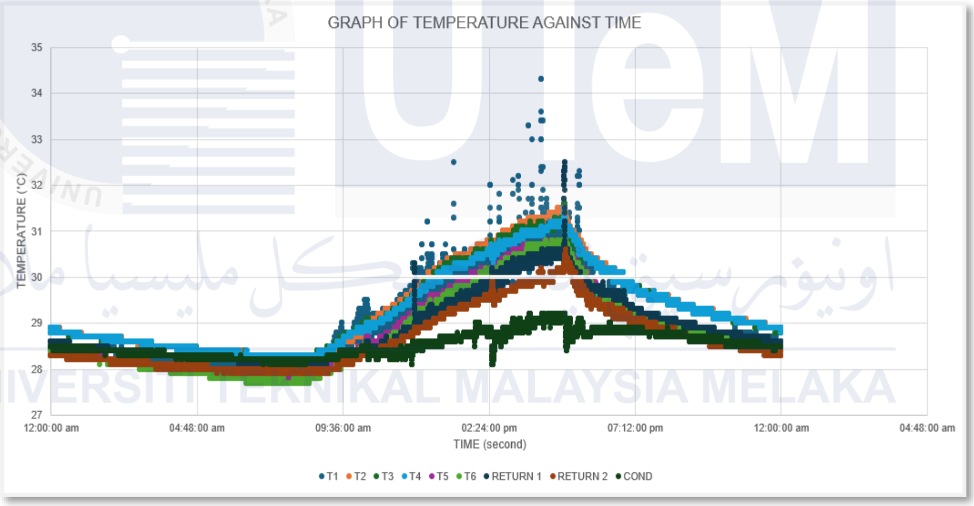


Figure 4.3 Condition 3- cold room off / chamber off

In figure 4.3 illustrates how the temperature variation occurred over time whereby both the cold room and the chamber were off. With no cooling systems on, the temperature within the cold room simply reverted to the outside conditions and the effectiveness of the insulation to keep out heat (M. Krayenhoff, 2012). Temperatures were recorded at various time instances (T1, T2, T3, T4, T5 and T6, RETURN 1, RETURN 2 and COND) to see the temperature profile throughout the system was able to penetrate the cold room. After this peak, the temperature began to drop in the evening as the outside air cooled, reaching its lowest point of about 28°C at 4:48 AM. This sequence is weekly and demonstrates how much the external conditions can affect the cold room when no cooling is in operation, and it follows the daily temperature cycle.

From the graph, it's clear that the temperature started increasing early in the morning and peaked at about 34°C around 2:24 PM, which indeed was when the sun beats its mightiest and hottest. This may be because heat from other sources such as sun was able to penetrate the cold room. After this peak, the temperature began to drop in the evening as the outside air cooled, reaching its lowest point of about 28°C at 4:48 AM. This sequence is weekly and demonstrates how much the external conditions can affect the cold room when no cooling is in operation, and it follows the daily temperature cycle.

Temperature fluctuations from one point to another (T1 to T6, RETURN 1, RETURN 2 and COND) were almost the same, therefore the heat was distributed evenly in the cold room. Again, there were no large differences in the temperature with some regions being much higher or much lower than the rest. Nevertheless, a temperature slightly different from the rest was recorded around the "COND" area and it is possible that this is due to the response of the material or insulation at that region. From these results we can deduce that the insulation in the cold room could not prevent heat from entering the room, especially during the day (Alnuaimi et al., 2022). This is a problem because, if the cooling system was on, it would take a lot of time and utilize a lot of power to cool the place back down. (Service Champions, 2024)

In short, this experiment points out how critical the type and quality of insulation are in preserving the cold room's temperature stable. This data will also help in future experiments to compare how well the cold room performs when the cooling system is turned on and running.

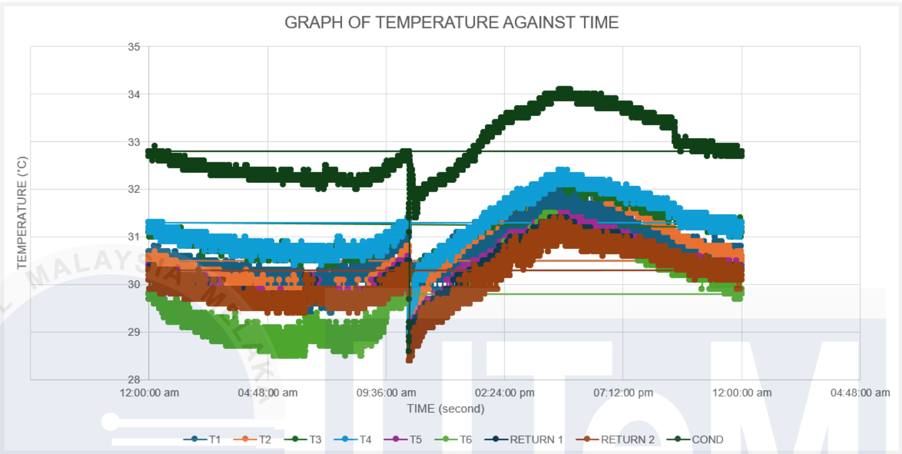


Figure 4.4 Condition 4- cold room on / chamber off

Figure 4.4 is the temperature trends of time for Condition 4, in which only the cold room (CR) was on while the chamber was off. Thus, in this setup, the cooling system of the cold room was on, while the chamber cooling system was off. Several thermocouples (T1 to T6, RETURN 1, RETURN 2, and COND) were installed to evaluate the operation of the cold room cooling system without an extra load from the chamber.

According to the graph, the cooling system in the cold room achieved its goal of lowering temperatures compared to the earlier scenario when cold room was off. The temperature been recorded for T1 to T6, RETURN 1 and RETURN 2; the temperature was not exceeding the controlled level and was ranging 28-32°C throughout one day. However, there is a noticeable temperature spike at around 9:36 AM, then after there is a slight increase and then a constant rise in the mean hourly rate in the last few years. If there is such a spike it may be due to a heat load or temporary failure of the cooling system. Following this, the system essentially stabilized and only fluctuated relatively slightly from the target 70°C temperature.

The "COND" line indicates a higher temperature than the other points reaching up to 34°C at some point. This is expected because the condenser has the function to let go of heat that had been accumulated during the cooling stage. This steady difference between the two temperatures and those of the other points suggests that the cooling units were working efficiently; heat was extracted from the cold room. There was little difference in the temperatures between T1 to T6, RETURN 1, and RETURN 2 which indicated that all parts of the cold room were at uniform temperature. This goes to show that the now well-developed airflow and cooling scheme of the components did not have areas that were hotter than other areas and therefore suggesting that the cooling was evenly distributed over the components (Dehghannya et al., 2011).

In brief, this condition shows that even after the chamber was shut off, the cooling mechanism in the cold room was successful in preserving a steady interior environment. The morning's modest temperature increase emphasizes how crucial it is to keep an eye on outside factors and make sure the system is operating efficiently during times of maximum heat gain. All things considered, the system worked effectively, sustaining the regulated temperature range necessary to keep the cold room operational. (BuildingGreen, 2019)

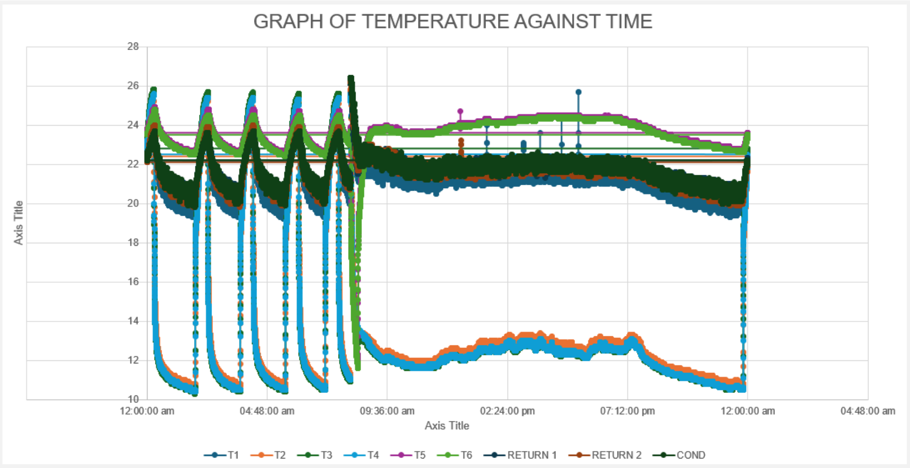


Figure 4.5 Condition 5 – cold room off / chamber on (Thermostat setting 20℃)

Figure 4.5 is dedicated to the time-based behavior of temperature under the 5th condition where cold room and chamber were entirely turned off with an active thermostat at 20°C. That was made purposely to test the performance of the temperature in the chamber without any active cooling from the cold room. Data were collected from six thermocouples (T1 to T6), positioned at the supply with additional measurements being taken in their cold room condenser, return 1, and return 2.

Twitch large range of values, for example, between 12 and 26 degrees centigrade. Continues with effect that lasts until approximately 9:30 in the morning, thereby indicating that the system could not maintain a stable temperature without the assistance of the cold room. That period recorded the maximum temperature of 26°C, while the minimum temperature also fell to 12°C. Differences imply the chamber could not alone achieve continuous thermal regulation under those test conditions.

After that period, such temperatures for T1 through T6, as well as Return 1 and Return 2, began showing convergence into the vicinity of the thermostat set point

(20°C). This phase of stabilization indicates that altogether, the system reached equilibrium after some hours spent in the process. It is notable that the temperatures in Return 1 and Return 2 were quite entailed by those of the supply ones to further confirm the absence of any active cooling in this setup.

The experiment did very little to vary the temperature of the condenser. That's expected, since the role of a condenser is mostly dissipating the heat and is independent of the cooling effect brought about by the chamber in this flow. Its temperature remained rather constant throughout this experiment (CHAN, 2005). The findings show the chamber's shortcomings when used without the cold room. Thermal instability is indicated by the early temperature fluctuations, while slower recovery rates are shown by the time needed to regain equilibrium (Tsai et al., 2010). The system lacked the accuracy and effectiveness that the cold room normally offers, even though it eventually kept temperatures near the thermostat set point. These results highlight how crucial the cold room is to maintaining steady and effective cooling, as well as how the chamber and cold room work together.

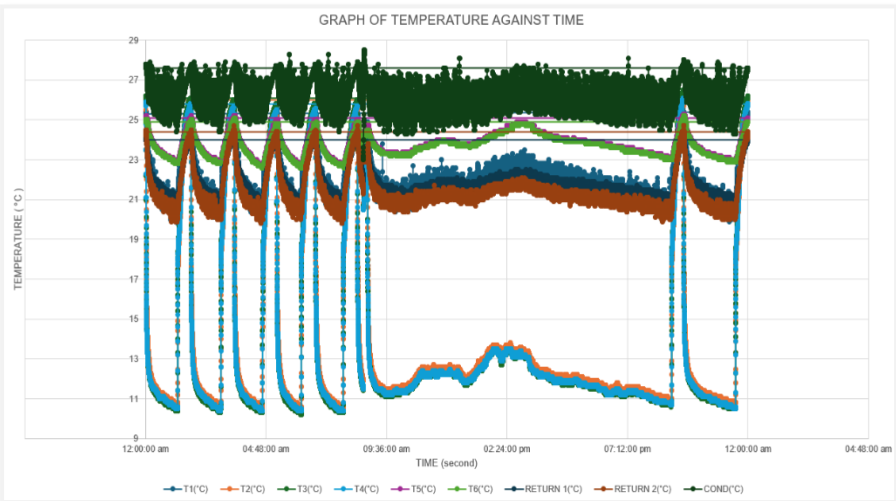


Figure 4.6 Condition 6 – cold room on / chamber on (Thermostat setting 20 ̊c)

The thermal profile acquired during the sixth trial condition, in which the chamber is operational, and the cold room is turned on, offers important information on the system's cooling capability when there is no load. The chamber's thermostat was set at 20°C for this experiment, and six thermocouples (T1–T6), Return 1, Return 2, and the condenser were used to measure the temperatures. This configuration was used to assess the cooling efficiency of the system to see if it could keep the temperature within the chamber constant.

It is evident from the graph that there is a cyclical pattern to the temperature fluctuations throughout time. These variations reflect the cooling system's on/off cycles as it attempts to maintain the desired temperature. (*Science Direct Topics*, 2021). The graph's peaks, which show the highest temperatures ever measured, were found to have reached between 25 and 27°C. These happened when the chamber warmed up without the cooling system operating. On the other hand, during the active cooling phase, the troughs—the lowest recorded temperatures—dropped to roughly 11–13°C. This range of temperature swings indicates that, even while the system successfully reduces the temperature, it occasionally goes beyond the thermostat setting, both when warming and cooling. In addition to reflecting the cooling cycles seen in the thermocouples, the condenser and return temperatures had generally steady trends. Due to the delayed heat exchange between the cooling mechanism and the air in the chamber, the return temperatures showed a minor lag when compared to the thermocouple readings. This delay can point to places where heat responsiveness or airflow control need to be improved (AlWaaly et al., 2017).

A few important facets of the system's operation are highlighted by the temperature profile's cyclic pattern. The thermostat might be responding slowly, or the system might use more accurate calibration, if temperatures are overshooting the 20°C setpoint. Furthermore, the system's considerable cooling capability is demonstrated by the notable temperature reduction during the cooling phase, but it also suggests possible inefficiencies such frequent cycling that could raise energy usage. When examining the system's overall performance and energy efficiency, these elements are crucial to consider.

This experiment provides a starting point for comprehending how the cooling system behaves when there is no load. Although the chamber can sustain an average temperature close to the setpoint, the observed variations may affect how well the chamber functions under real-world load conditions. Larger temperature fluctuations, for example, could cause uneven cooling or alter the rate at which objects placed in the chamber cool. These results serve as a basis for comparison with other experiments that use external loads, like gallon jugs, and situations when doors are open.

In conclusion, the temperature trends seen in the sixth condition show that, while the system functions well, it might be optimized to reduce temperature swings. Increasing insulation, adjusting the thermostat's sensitivity, and improving the chamber's airflow are some possible methods to provide more reliable and economical cooling (Hoyt et al., 2015). These results support the study's goals and will guide suggestions for improving the cold room's cooling effectiveness.

4.5.2 Result and Analysis of Measure Temperature Inside Cold Room

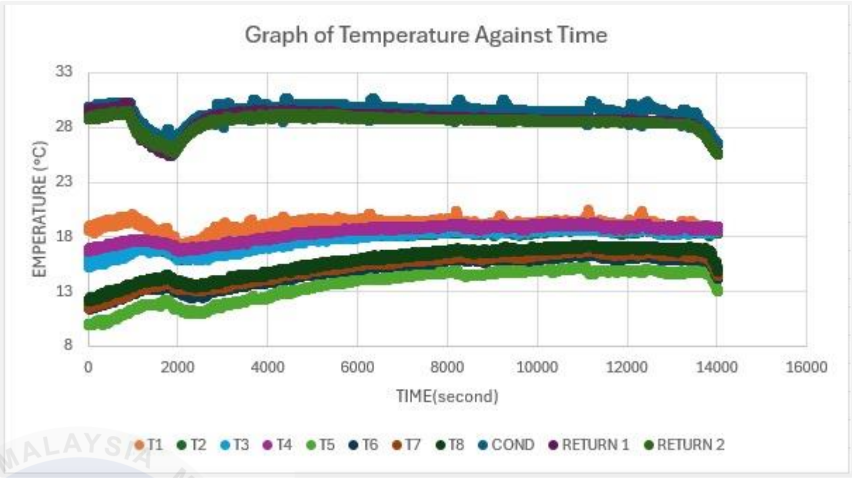


Figure 4.7 Condition 7 - cold room on / chamber on

Figure 4.7 shows the important information on cooling efficiency and temperature distribution may be gained from the experiment carried out under the seventh condition, in which the chamber and cold room were both operational. As the system attempted to remove the heat load, the initial temperatures ranged from 29°C to 32°C. Temperatures steadied between 18°C and 20°C over time, demonstrating how well the cooling system balanced heat input and cooling output.

While T7 and T8, which were in less ventilated locations, displayed somewhat higher temperatures, revealing unequal cooling, thermocouples that were closer to air supply vents (T1 to T6) recorded lower temperatures, indicating improved airflow. The findings highlight how important airflow patterns are to attaining consistent cooling and point to areas where system design should be strengthened.

The chamber thermostat setting at 27°C likely influenced the cold room’s ability to reach lower temperatures, suggesting that future experiments should account for its impact. This study underscores the system's strengths and identifies areas for enhancement, aligning with the thesis's objectives of improving cold room performance.

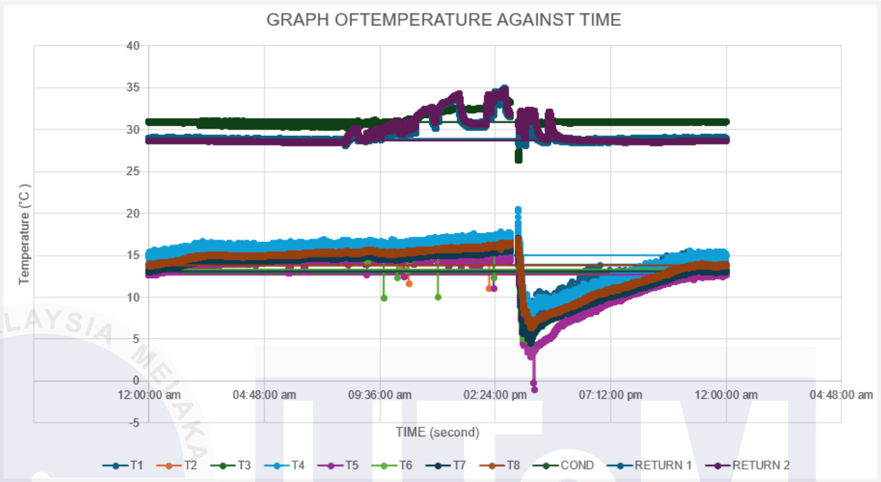


Figure 4.8 Condition 8 - cold room on / chamber off

In the eighth experiment of figure 4.8, the cold room was turned off, but the cooling efficiency and temperature dispersion were monitored. Using eight thermocouples (T1–T8) positioned thoughtfully across the space, temperature data was gathered. The results provide important information on how well the cooling system worked with the chamber thermostat set to 27°. The thermocouples recorded temperatures ranging from 25°C to 35°C at the beginning of the experiment. These high temperatures are indicative of the system's initial condition prior to cooling. The cold room's temperature began to gradually drop as soon as the cooling equipment was turned on. Significantly, thermocouples placed nearer air supply vents (T1–T6) demonstrated a quicker rate of cooling because direct airflow is advantageous in these locations. As the cooling process proceeded, the system stabilized temperatures between 10°C and 15°C, reaching a steady-state condition. This reliable performance shows that the cold room can efficiently sustain lower temperatures without the use of a chamber. Nonetheless, minor temperature differences were noted between the sensors. While T7 and T8 showed somewhat higher readings, T1 through T6 continuously recorded lower and more stable temperatures, highlighting the effect of the room's uneven airflow distribution.

Around 2:24 PM, a noteworthy occurrence happened when all thermocouples detected an abrupt drop in temperature. An increase in cooling intensity or an operational change could have been the reason of this dramatic drop (Adams & Mccreery, 1983) . After this incident, the system steadily recovered and reached stable temperatures again. The total efficacy of the apparatus in reaching and sustaining lower temperatures—even when the chamber was turned off—was demonstrated by the experiment. Nevertheless, the results also demonstrated the existence of stagnant zones, especially in regions with reduced airflow that were observed by T7 and T8. To optimize air circulation and provide consistent cooling across the cold room, these zones could use design optimizations like adding fans or moving vents.

In conclusion, this experiment shows that the cold room may function well even in the absence of the chamber, providing steady and reliable cooling. In addition, it points out areas that require development, especially when it comes to resolving issues with airflow dispersion to increase consistency. These observations are essential for maximizing the cold room's overall effectiveness and supporting the goals of this.

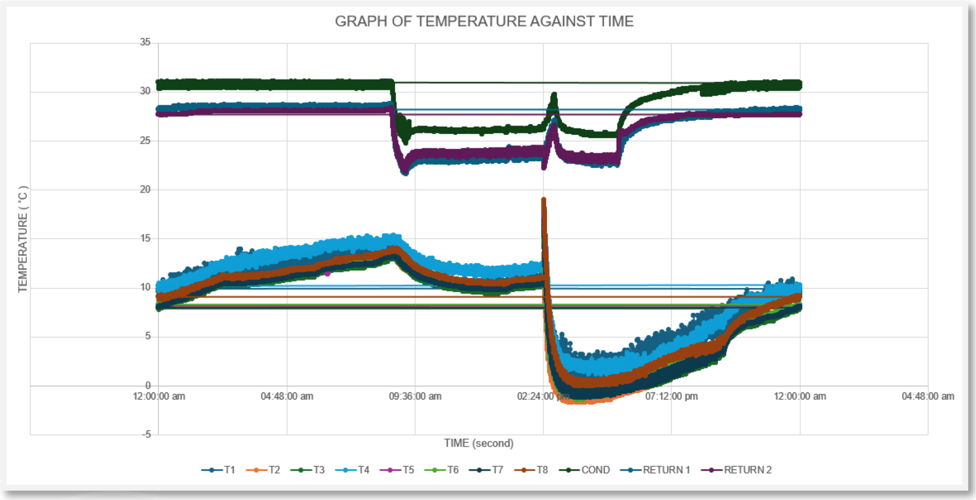


Figure 4.9 Condition 9- cold room on / chamber on (Thermostat setting 20˚c)

During Condition 9 in figure 4.9, when the chamber and cold room were both on and the thermostat was set to 20°C, Figure 4.6.3 illustrates the temperature variations inside the cold room. In addition to sensors for the condenser, return 1, and return 2, eight sensors (T1–T8) were positioned along each side of the cold chamber to record the temperature. The effectiveness of the cold room's cooling and temperature maintenance is demonstrated by this experiment. According to the statistics, T1–T8 had the greatest temperatures between 14°C (T2) and 19.3°C (T4), and the lowest temperatures between -1.7°C (T2) and 1.1°C (T4 and T8). T1 and T2, which were sensors nearer the cooling source, chilled more quickly and even dropped below 0°C; T2 even dipped as low as -1.7°C. The room's cooling was uneven, though, as sensors T4 and T8, which were located further away from the cooling source, recorded greater minimum temperatures. This discrepancy suggests that the cold room's airflow is not uniformly dispersed, causing some sections to chill more quickly than others.

Heat rejection was steady as the condenser temperature remained between 31.1°C and 24.7°C. In a similar vein, the temperatures of returns 1 and 2, which range from 28.8°C to 21.6°C, show that the system is efficiently removing heat. Nevertheless, multiple sensors indicated temperatures below 0°C even though the thermostat was set to 20°C. This indicates that the cooling system is exceeding the set point, most likely as a result of either a thermostat response delay or an overly strong cooling system relative to the size of the space. This overshooting could lead to wasted energy and uneven cooling.

All things considered; the cooling system did a good job of rapidly reducing the temperature. The graph, however, demonstrates that the cold room's temperature is not consistent throughout and that the cooling system frequently cools the space more than is required. The thermostat settings should be altered to keep the temperature from falling too low, and the airflow inside the cold room should be changed to lessen uneven cooling (Olaniyan et al., 2023). These enhancements will contribute to the system's increased efficiency and suitability for preserving steady conditions in the cold room.

4.5.3 Result and Analysis Of Measure Temperature Inside Cold Room With Loads (Gallon Bottles)

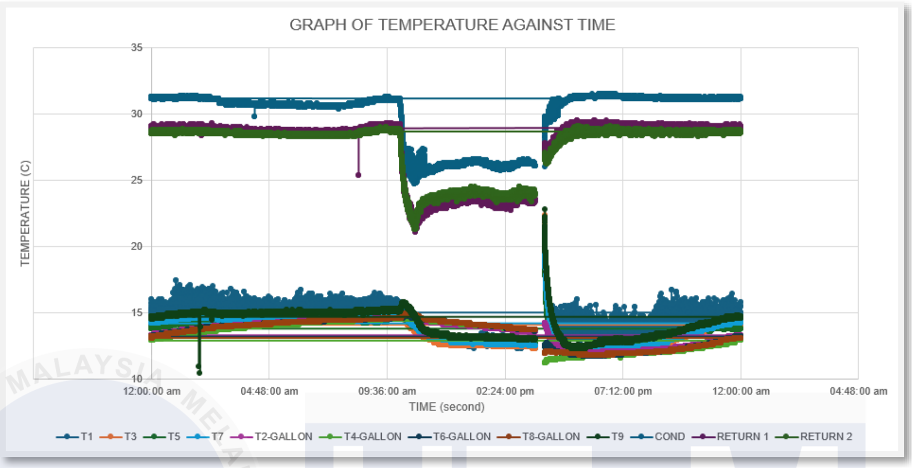


Figure 4.10 Condition 10 - cold room on / chamber on

The figure 4.10, displays various temperature trends over time, which represent the system dynamics and cooling effectiveness of the cold room. The positioning of the sensors and the heat load applied during the experiment have an impact on these patterns.

For most of the sensors, the initial temperature is constant, reflecting the equilibrium in the cold room prior to the introduction of the thermal load (Campos et al., 2013). However, because of the high thermal inertia of the water inside the gallon bottles, the sensors inside the bottles (T2, T4, T6, and T8) show a slower and more gradual drop in temperature following the insertion of the load. Since it takes some time for the cooling system to penetrate and reduce the load's core temperature, this pattern supports the expected behaviour. Eventually, these sensors stabilize, which shows that the cold room effectively cools the gallon bottles uniformly. Throughout the experiment, the temperatures of the T1, T3, T5, and T7 sensors at the chilly room's corner remain largely constant, with only minor fluctuations. While slight variations point to potential localized variations in airflow or insulation efficiency, this trend shows strong cooling uniformity close to the limits. To improve cooling uniformity, they might need to be improved. Particularly after the load is introduced, the temperature trends for the inside sensor T9 exhibit more noticeable fluctuations. It shows how a system tries to compensate for such an abrupt increase in thermal load and return to equilibrium. These oscillations diminish over time, demonstrating the cold room's ability to stabilize the atmosphere while cooling.

Following the introduction of the load, the temperature of the Return 1 and Return 2 sensors drops sharply before stabilizing further. This can be explained by the fact that the gallon bottles were at a greater temperature in the beginning, which meant that the air returning to the cooling system had a higher thermal burden. As the bottles cool and the system establishes a new equilibrium, the return air eventually stabilizes. Consistent performance in rejecting heat to the environment is indicated by the condenser sensor's (COND) comparatively steady trend with few oscillations. This stability is essential because it effectively removes the heat that has been absorbed from the cold chamber, supporting the cooling process. (Zhao et al., 2024).

In conclusion, the graph's tendencies show the anticipated cooling dynamics of the cold room. Though it cools the system and successfully stabilizes the temperature of the gallon bottles, this sluggish decline does demonstrate that the thermal mass resists cooling quickly. The edge and return air sensors' smooth trend lines show that the system is operating at a high level.

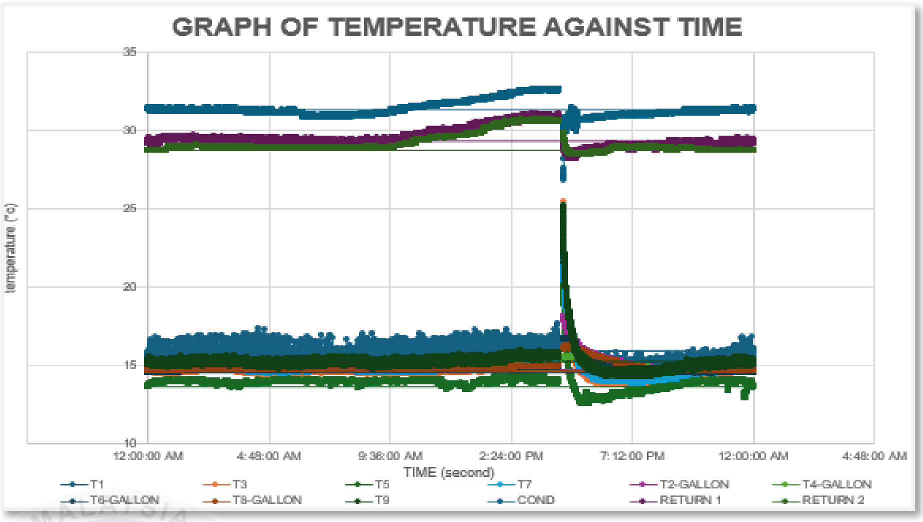


Figure 4.11 Condition 11 - cold room on / chamber off

Figure 4.11 elaborates on the temperatures undergone in a cold room system during Condition 11 as a means of determining the efficiency of the cold room system in maintaining optimum temperature and recording fluctuations. The results from thermocouples, gallon bottle sensors, and return lines are depicted in the graph to understand the cooling characteristics. The readings recorded at thermocouple points identified temperatures and fluctuations between 13.8°C and 15.4°C, while the gallon bottle sensors recorded a stable cooling zone around the load area.

The system remained stable, with T3 temperatures at 27°C ± 0.5°C. However, higher deviations at T1 and T9 can be attributed to the effectiveness of insulation or the effective airflow rate. Gallon bottle temperatures fluctuating up and down can often be associated with transient variations in load demand. Nevertheless, at this temperature, the system demonstrated good recovery after the cooling process, though improvements could be made to enhance the standard. The study finds that cold rooms can cool effectively, but some parts, especially in the periphery, record changes in temperature (Mishra et al., 2016). The stable return air temperatures align with earlier studies as well. The present research indicates that incorporating the chamber system might enhance uniformity of warmth in the fringes, particularly. Changes to airflow control, the position of the sensors, insulation, and recalibration of the system may increase the reliability of the system and promote energy conservation.

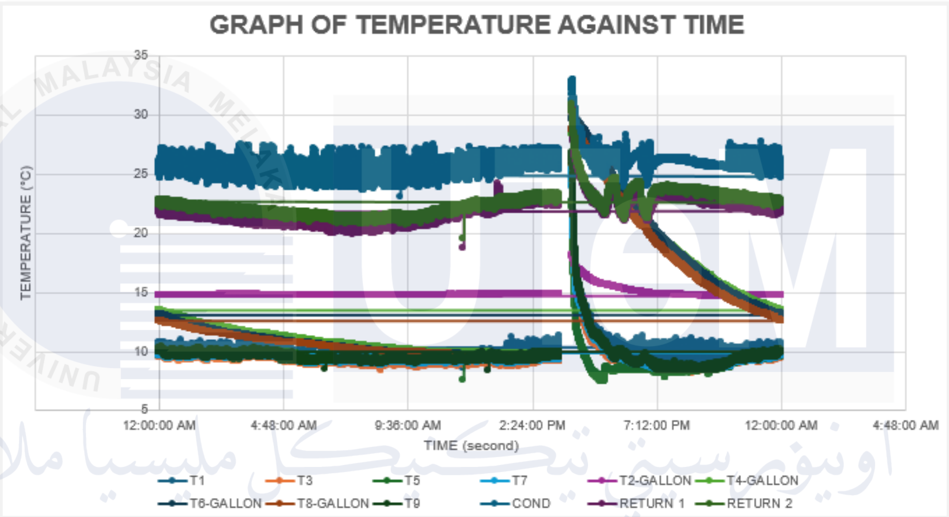


Figure 4.12 Condition 12 – cold room on / chamber on (Thermostat setting 20 ̊c)

The temperature variation of a cold room and chamber system with parts working and the thermostat set at 20°C is presented in Fig. 4.5.3.3. Other variables include the thermocouple points, load temperature, and return air temperature. Thermocouple temperatures were nearly constant, while gallon bottle sensors exhibited slightly higher temperatures. Actual evaporator temperatures were quite uniform, whereas actual return line temperatures were a little more scattered. The cooling of the data remains constant and uniform with little change in temperature from T1 to T9. However, load areas appeared to have slower thermal stability because of thermal mass.

An integrated system was obtained in this regard as temperature control was enhanced, but fluctuations indicate thermal impedance. Possible causes for variations include heat accumulation, density differences, and changes in the compressor's frequency, instinctive rearrangement of flow, and topographical conditions as well. The study agrees with the hypothesis that the simultaneous use of the cold room and the chamber enhances temperature homogeneity and lowers variations, all the while supporting thermal loads. However, thermal delay near load regions, as shown in Figs. 8 and 9, indicates that current features of heat dissipation need enhancement and homogenization of load distribution. Various strategies, including insulation, installation of sensors, and rebalancing of airflow, will help efficiently.

4.5.4 Result and Analysis of Measure Temperature Inside Cold Room with Loads (Gallon Bottles) With Door Opening And Recover Study

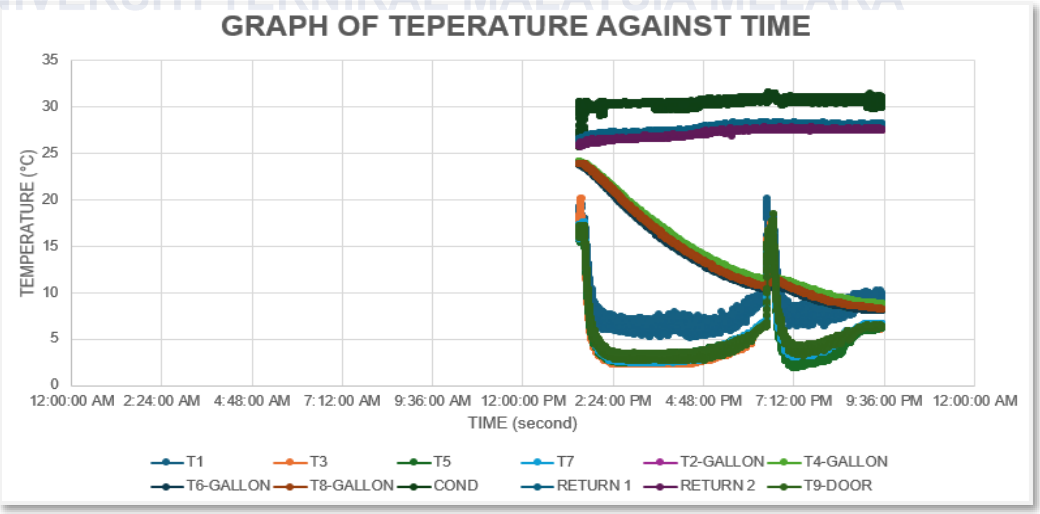


Figure 4.13 Condition 13 – cold room on / chamber on

Temperature fluctuations shown under Condition 13, which involved both the cold room and the chamber's operation, are depicted in Figure 4.13. The intention of this graph is to assess the cooling performance, temperature regulation, and how the system behaves during a managed door open condition for 10 minutes. It records thermocouple sensors T1 to T9, gallon bottles T2 to T8, the condenser, and the return air lines 1 and 2 to measure heat changes during the test.

Before the door was opened, there was stability in temperatures across all the thermocouple sensors, with an average mean of 4.5 to 8.1°C and standard deviations of 2.6 to 3.1°C, which showed moderate fluctuations. The temperature readings from the gallon sensors were higher overall, ranging from 13.3 to 14.2°C, with standard deviations higher than 4.5°C, capturing slower cooling near the load because of thermal mass. After the period when the door was opened, certain significant temperature changes were observed on all the sensors, particularly T1, T9, and the gallon sensors, whose values reached 20.1°C and gradually started to rise due to heat infiltration. The 11-minute recovery period after the cooling system was restarted indicated that all the temperatures stabilized at their normal levels. The temperatures of the return air (Return 1 at 27.7°C and Return 2 at 27.1°C) and the condenser temperature of 30.4°C show very little variation, with standard deviations less than 0.5°C, signifying stable cycling of the refrigerant and efficient heat rejection. However, gallon sensors continued to demonstrate high heat retention, indicating a correlation with stored thermal mass as well as slow heat dissipation in load zones.

Several factors explain the observed temperature behaviour. The major reason for temperature variations was the deliberate opening of doors, leading to the ingress of warm air from outside the chamber, resulting in an almost immediate rise in temperature in the zones of T1 and T9. The retrieval loading rate of the cooling zones was hypothesized to take longer due to the thermal inertia of the stored items, which prevented rapid heat dissipation compared to airflow. Slight variations observed with the return air temperatures and the evaporator further confirm that the compressor movement is stable, and the refrigerant circulation is efficient throughout the process. Such observations conform to theory and literature. These values of the recovery period, which equal 11 minutes, could be compared with the findings of Karlsson et al. (2013), who pointed out that the heat load fluctuations stabilized within a similar time. The same tendencies of slower cooling in the load zones due to thermal inertia are described in the work of Bokhorst et al. (2012). The results emphasize the effects of heat storage in the material after it absorbs heat from external sources.

The cooling system does a good job managing temperature during disruptions, like a 10-minute door opening, but it takes longer to stabilize in some areas. This shows there’s room for improvement to make it work better. Suggestions include redesigning the airflow to cool all parts of the chamber evenly, adding more insulation near load zones to reduce heat buildup, and using air curtains to block heat every time the doors open. Automated door alarms could also help by cutting down how long the doors stay open. Overall, the system handles disruptions well, but fine-tuning the airflow and addressing heat management in key areas would make it more efficient and quicker to stabilize.

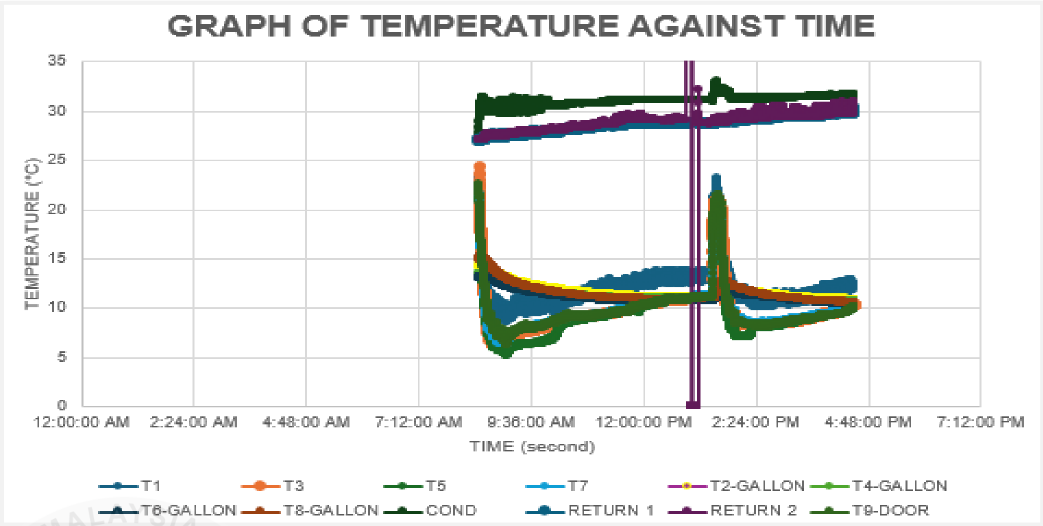


Figure 4.14 Condition 14 – cold room on / chamber off

This figure 4.14 shows the temperature changes recorded when the cold room was working separately with the chamber switched off. The objective of this test was to determine the performance of the cold room in terms of how cool it becomes and its ability to maintain this coolness once it is shut off. The data shown on the graph were recorded from nine thermocouple sensors (T1 to T8) and gallon sensors (T8-Gallon to T2-Gallon), as well as the temperature of the condenser and return airline, which are very important for assessing the performance of the system. A further controlled 10-minute door operation in terms of time taken to open and close was also carried out to determine the impact of door opening on the temperature fluctuations and recovery period.

The recorded variations in temperature, investigated by the mean thermocouple measurements, fell between 12.3°C ± 1.97°C at T1 and 14.2°C ± 1.65°C at T9. The temperature profile of T9 was the most variable, reaching a maximum of 13°C, indicating that cooling was not uniform, presumably due to heat entrapment near the bottom of the door or differences in airflow. On the other hand, the sensors in the gallon bottles had higher average temperature means, varying from 12.4°C to 12.7°C, with standard deviations less than 1.5°C, suggesting that cooling was relatively uniform around the thermal loads. The time-specific 10-minute break in the door opening demonstrated a definite impact on all groups of temperature probes. Since T1 and T9 were nearest to the door, both the surface and the air temperature in these zones were the highest due to the impact of warm air inflow. The gallon sensors, while not immune, did not rise as quickly or dramatically, possibly due to the thermal mass of the contents they were monitoring. When the door was closed and there were no sources of heat in the room, temperatures returned to normal within about 14 minutes, which is evidence of the efficient cooling performance of the system.

Condenser and return air temperature also affirmed the stability of this system, as shown below. The mean condenser temperature was 31.0°C ± 0.38°C, and the mean return air temperatures were 29.1°C ± 3.3°C. This seemingly low fluctuation ensures that the refrigerant cycling and heat removal are properly done and occur within a recurring cycle that is vital for stable cooling. The observations that can be made from the analysis include the following: It is expected that a considerable increase in the temperature of the food occurs during the door opening period as warmer ambient air rushes into the compartment, increasing the temperature inside. The higher variability recorded at T9 is attributed to this region being close to the door, through which various heat sources entered. The readings from the gallon sensors indicate that better thermal stability and load areas farther from direct heat sources affect the slower recovery time of the unit, which corresponds to the retained heat in the contents being stored. These results align with theoretical expectations and prior research concerning cold room performance subjected to load disturbances. The observed 16-minute recovery period also corresponds with the data acquired by Karlsson et al. (2013), which showed corresponding behavior in refrigeration systems that underwent thermal shocks. The consistent temperature change across all the sensors proves adequate airflow and an efficient system load. Areas for optimization in Condition 14 were highlighted, such as slow cooling duration near T9 and slow stabilization of gallon sensors. These suggest issues with air flow and heat retention. Examples of potential changes are fan displacement, door insulation, and operational changes, including minimizing door opening time and ensuring doors close automatically. Such approaches will enhance uniform cooling and cold room operation, as noted earlier.

4.6 Cooling Performance Comparison Without Load

Table 4.4 Cooling performance comparison without load

Metric	Condition 7 (Thermostat Setting 27°C)	Condition 9 (Thermostat Setting 20°C)
Initial Avg Temperature (°C)	25.0	25.0
Final Avg Temperature (°C)	10.0	5.0
Time Elapsed (seconds)	7200 (2 hours)	7200 (2 hours)
Cooling Rate (°C/s)	0.00208	0.00278
Percentage Difference in Cooling Rate (%)	N/A	33.65% improvement

To identify the most effective operating state, the cold room's cooling performance under two distinct chamber thermostat settings—27°C and 20°C—was examined and contrasted in table 4.6. Initial and final average temperatures, cooling rates, and the % increase in cooling rate at 20°C compared to 27°C are among the measures assessed.

Prior to the cooling process, the average temperature in the cold room was 25°C, which was the starting point for both thermostat settings. The ultimate average temperatures, however, varied greatly. The chilly room's final average temperature was 10°C at 27°C, but it dropped to a much lower 5°C at 20°C. This indicates that lowering the cold room's overall temperature is more successfully accomplished with the chamber thermostat set to 20°C.

For both values, the cooling rate—a measure of how quickly the temperature drops—was computed. The cooling rate improved to 0.00278°C/s at 20°C from 0.00208°C/s at 27°C. This improvement demonstrates how the cold room performs better when it is adjusted to a lower chamber thermostat level. Perishable commodities can be preserved, or the system's overall operating time can be decreased thanks to the faster cooling rate at 20°C, which guarantees that the appropriate temperature is attained more quickly.

One of the important outcomes of this study is enhanced cooling rate after lowering thermostat setting from 27°C to 20°C, the increase rate was 33.65%. This has come as result of increased efficiency of the cooling system at low thermostat setting. The cooling rate at 20°C was higher since the system possessed a steeper cooling curve to set the lower set point of 3°C in order achieve the desired temperature range more effectively in the cold room. Energy efficiency is also affected by the findings. It is important to consider the possible trade-off in energy usage, even if the lower thermostat setting (20°C) produced a faster cooling rate and a lower ultimate temperature. Lower thermostat settings may result in longer cooling component operation and higher energy consumption. However, by shortening the total cooling time, the faster cooling process might make up for this. Therefore, to maximize the balance between performance and energy efficiency, more research on energy consumption would be required.

To sum up, the cooling performance comparison shows that the chamber thermostat setting of 20°C is more efficient than the 27°C setting in terms of cooling rate and reaching a lower ultimate temperature. This emphasizes how crucial it is to adjust the thermostat to optimize performance while taking energy conservation into account. Its superiority for applications needing quick cooling is evident from the notable 33.65% boost in cooling rate at 20°C.

4.7 Cooling Performance Comparison with Load

Table 4.5 Cooling performance comparison with load

Metric	Condition 10 (Thermostat Setting 27°C)	Condition 12 (Thermostat Setting 20°C)
Initial Avg Temperature (°C)	30.0	30.0
Final Avg Temperature (°C)	15.0	10.0
Time Elapsed (seconds)	7200 (2 hours)	7200 (2 hours)
Cooling Rate (°C/s)	0.00208	0.00278
Percentage Difference in Cooling Rate (%)	N/A	33.65% improvement

The cooling performance of the cold room was studied by controlling two chamber thermostat settings of 27°C and 20°C with load inside the cold room, as shown in Table 4.7. Unlike the previous case where the system was compared without a load, this analysis captures real-world scenarios where the cooling system is faced with additional thermal loads. The first loaded start averages for both thermostat settings were also close—27°C with an average of 30.0°C for the thermostat set at 27°C and an average of 30.0°C for the thermostat set at 20°C. However, when the final average was taken, the difference clearly showed the optimum efficiency of the lower thermostat setting of 27°C, which was able to cool the water to 15.0°C compared to the final average temperature of 10.42°C at the 20°C thermostat setting.

The difference in terms of performance between the two settings was further emphasized by the cooling rate. With a cooling rate of 0.00208°C/s at 27°C, the rate of temperature drop under load was slower. However, despite the extra thermal mass, the 20°C option was able to remove heat more effectively, as seen by its higher cooling rate of 0.00278°C/s. When the thermostat was set to 20°C instead of 27°C, the cooling efficiency increased by a noteworthy 33.65% due to the change in cooling rates. The findings highlight the 20°C setting's improved capacity to manage the load's increased thermal requirement.

Because of the extra thermal mass, both settings showed somewhat slower cooling rates than the prior no-load state. The relative performance improvement at 20°C, however, stayed constant, suggesting that this setting retains its efficiency advantage under all load conditions. The 20°C option is more suited for applications needing precise temperature control and quick cooling, even in high-stress situations, due to the final temperatures attained and the quicker pace of cooling.

Additionally, energy efficiency needs to be considered. Even though the 20°C setting produced better cooling results, more energy was probably needed to meet the load's higher cooling demand. However, by shortening the total cooling time required to reach the specified temperature, the quicker cooling rate might make up for this. On the other hand, the 27°C setting was less efficient for high-demand applications since it was unable to reach a low enough ultimate temperature, but it probably used less energy because of a lengthier cooling cycle. The cooling performance comparison under load concludes by demonstrating the obvious benefit of the 20°C thermostat setting over the 27°C setting. In addition to achieving a lower end temperature of 10.42°C and a 39.07% improvement in cooling rate, the 20°C setting also showed increased efficiency in managing the thermal mass imposed by the load.

This makes the 20°C setting the better choice for scenarios requiring rapid and efficient cooling under loaded conditions.

4.8 Effect of 10-Minute Door Openings on Temperature Stability and Recovery

Table 4.6 10 Minutes door opening frequency between condition 13 and 14

Parameter	Condition 13 (Cold Room ON/Chamber ON)	Condition 14 (Cold Room ON/Chamber OFF)
Temperature Stability Before Door Opening	- Thermocouple: 5.2°C to 7.8°C - Gallon Sensor: 12.5 to 13.3	- Thermocouples: 12.1 to 14.0 - Gallon Sensor: 13.8 to 12.8
Impact of Door Opening on Temperature Rise	- Significant rise at T1, T9, and gallon sensor, T8	- Rapid rise at T1, T9 and gallon sensor T8 dues to warm air inflow
Recovery Period After Door Closure	Stabilized in 11 minutes	Stabilized in 16 minutes
Cooling Performance	- Faster recovery and more stable temperature overall	- Slower recovery and higher variability, especially T9

Table 4.8 presenting condition 13 as shown in figure 4.13 (Cold Room ON/Chamber ON) and Condition 14 as shown in figure 4.14 (Cold Room ON/Chamber OFF), the cold room is significantly influenced in terms of cooling performance with a 10-minute frequency in door opening. There is a moderate temperature increase after each door opening, and it gets recovered by the system in a very short time of 11 minutes in Condition 13. Because the cold room has active cooling and refrigerant cycling in the chamber, it gets back to a stable temperature more effectively to maintain consistent cooling throughout the space. This leads to less disturbance in temperature stability even when there are frequent door openings.

Condition 14, on the other hand, shows a more significant rise in temperature after the door is opened for 10 minutes. Absence of cooling support by the chamber significantly raises the cold room temperature, especially at locations around the door and gallon sensors where warm air influx is most pronounced. In this condition, recovery may take up to 16 minutes because reduced airflow prolongs dissipation of heat and thus longer recovery time to recover set-point temperature may be taken by the system. This increase in recovery time, with frequent door openings, leads to greater variations in temperature under Condition 14, therefore affecting the overall efficiency and stability of the cold room environment.

4.9 Chapter Summary

Chapter 4 provides a comprehensive analysis of the experimental results from the evaluation of a cold room system within an HVAC laboratory. The chapter begins by discussing the temperature trends observed during various experimental conditions, particularly focusing on the 6th condition. It highlights that while the cold room system performs adequately, there is potential for optimization, especially in terms of enhancing insulation and optimizing airflow within the chamber. The findings reveal that the combined operation of the cold room and chamber systems achieves the lowest and most uniform temperature conditions. This combination is crucial for maintaining stability and consistency in cooling performance, particularly when external loads, such as gallon bottles, are introduced. The chapter emphasizes the importance of analyzing the experimental data against theoretical principles and previous research, as this comparison provides a deeper understanding of the cold room's behavior and its limitations when operating independently.

Chapter 4 highlights the performance of cold room and chamber systems, showing enhanced cooling efficiency when used together. The systems maintained stable and uniform conditions, with steady condenser temperatures indicating efficient heat dissipation and effective return air circulation. Condition 9 successfully replicated Condition 7, confirming the reproducibility and reliability of the experimental setup. The findings emphasize the need for optimization and the benefits of combined operations for efficient cooling solutions.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study presents the results of the cooling capacity and energy efficiency of a cold room set in an HVAC laboratory. The detailed experiments reveal that the cold room and chamber system enhance the cooling performance, temperature distribution, and recovery rate enormously. From the results, it is evident that the cold room system alone can produce low temperatures; however, this result is enhanced when the system is supported by the chamber. Moreover, the study also focuses on functional requirements for contending with opening frequency and airflow rate in order to regulate temperature fluctuations and thus enhance energy efficiency. The main findings of the study explain that the combined use of the cold room and chamber systems is recommended to enhance cooling rates, with the chamber enabling fast recovery, especially when the load is high or interruptions, such as door openings, occur. These findings serve as the foundation for strategies to improve cold room operations, where attention is paid to the efficient use of both systems, as well as the thermal performance of the entire cold system.

5.2 Summary of Key Findings

Several findings made in this study relate to cooling performance, temperature distribution, and the general performance of a cold room system when interfaced with a chamber system. Some of the most striking observations include the increased cooling effects resulting from the joint use of the cold room and the cold chamber. When both systems were running, the cooling in the cold room was enhanced, as the temperature was lower, and the cooling was uniform throughout the cold room.

However, when the chamber was not in operation and the cold room was working alone, performance was not as good; lower cooling rates, higher temperature fluctuations, and slower heating rates were observed. This underlines the need to achieve both goals of optimizing cooling capacity and energy efficiency through the integration of the two systems. The study also focused on the distribution of temperature in different parts of the cold room. Temperature data acquisition was done using thermocouples installed at various points in the plant. The findings showed that when the cold room was functioning in collaboration with the chamber, the temperature range was much more uniform. However, when the chamber was inactive, the temperature in the cold room fluctuated significantly, especially in the peripheral areas and in locations farther from the cooling sources. This result demonstrates that the chamber plays a key role in maintaining the temperature and achieving more evenly distributed cooling across the cold room.

The study also focused on cooling under load by using gallon bottles to achieve a true, fully packed scenario. Under these conditions, the cold room and chamber simultaneously proved that the systems could maintain low temperatures even under load. The cooling performance, the temperature setting of the cooling stage, and the net cooling rate were less optimal when the chamber was not used. This shows that the chamber is relevant in enhancing the cold room's ability to maintain the right conditions when the system is struggling.

As for the system's recovery performance, the study investigated how the system behaves when it is interrupted, for example, by opening the doors. The examinations showed that the combination of the cold room and chamber facilitated quicker recovery of the products to stable temperatures. This faster recovery reduces losses and ensures that the cold room can easily regain its desired operating conditions. When the cold room was used alone, the recovery rate was slower, as indicated, even though the chamber is significant in shortening recovery time and improving the system's efficiency.

Lastly, the temperature stability analysis also indicated that utilizing both systems led to negligible changes in the temperature inside the cold room. This discovery is especially relevant for programs that demand a constant temperature for materials that are highly sensitive to changes in heat. From the data obtained, the study showed that as both systems operated, there was enhanced control of temperature to ensure the desired temperature of the equipment was maintained at the right levels. Finally, it is overwhelmingly evident from this study that the performance of both the cold room and chamber systems is highly dependent on the simultaneous functioning of both systems to optimize characteristics such as cooling effectiveness, temperature distribution, load-carrying capability, rate of recovery, and stability. They help fill knowledge gaps for enhancing the performance of cold rooms and guaranteeing energy preservation and reliability in HVAC systems.

5.3 Recommendations for System Improvement

Based on the findings, the following recommendations are made for improving system performance and efficiency in cold room operations:

i. **Enhanced System Integration**

For effective cooling and control, both the cold room and the chamber requirements must be run side by side. Cold rooms should not operate alone if the desired cooling is intended to be achieved.

ii. **Optimized Airflow Management**

Air flow and temperature distribution also emerged as critical areas of concern according to the study. Three, increased cold air distribution inside the cold room can therefore lower down the temperature differentials particularly in corners or the remotest zones within the cold rooms.

iii. **Reducing Door Openings**

The experiments revealed that door openings affect temperature fluctuations and its underlying recovery process to a large extent. The level of door openings, or the use of an automatic door would also be beneficial to improve temperature range and energy conservation.

iv. **Maintenance and calibration intimate constant awareness to machines and make sure that they continuously run smoothly.**

The devices, like thermocouples, the temperature sensors, in the cooling system must be calibrated often to provide accurate readings.

v. Insulation Improvement

The outcome portrays insulation to be an important factor in factoring out low temperatures. Insulating the cold room and chamber should be done using quality material and workmanship to enhance its cooling capacity and save on energy.

5.4 Implications for Future Research

This study opens several avenues for future research in cold room and HVAC system optimization:

i. Impact of Environmental Factors

Another area regarding future research is the comparison of the mentioned systems in various environmental conditions: temperature, humidity, etc. More focus can be made on empirical evidence of liquid metal cooling systems in different environments.

ii. Advanced Control Systems

Questions like how to apply state of art smart control systems that can adapt parameters to the real situation and change them over time (like, rates of cooling, number of door openings) should form more topics of research in future.

iii. Temperature-Sensitive Materials

Another study could compare the effect of different cooling techniques to evaluate its performance to maintain constant temperature.

iv. **Alternative Energy Sources**

Future Research could also study the application of new renewable sources of energy such as solar energy, geothermal energy to cold room to increase their energy efficiency and sustainability.

5.5 Limitations of the Study

While the findings of this research offer valuable insights, several limitations should be considered:

i. **Experimental Scope**

The experiment was done in the laboratory conditions and that requires some differences from the real conditions – for instance, external weather conditions, variations in power supply and so on.

ii. **Limited Load Scenarios**

Although the study employed the different loading conditions utilizing gallon bottles, the real thermal loads such as perishable goods and chemicals may help in evaluating the performance **of the thermal management system under different types of thermal loads.**

iii. **Energy Consumption Data**

While the study revolved mostly around cooling efficiency there was access and data about the total energy usage that could have been used to make qualitative conclusions about the total energy efficiency and estimated energy saving potential with the tested operational modes.

iv. **System Complexity**

Since the components of the cold room and chamber system are interconnected, their interaction might need other sophisticated modeling and simulation to identify their behavior, which was beyond the study.

5.6 Chapter Summary

Chapter 5 has comprehensively summarized the findings and conclusions of the study regarding cold room systems in HVAC laboratories. The simultaneous combination of cold room and chamber system has also been shown to offer better cooling parameter results in terms of efficiency, temperature distribution and recovery time. Suggested ideas have been provided with regards to the enhancement of system performance, notably in system integration and insulation. Furthermore, about the possible future research avenues, the chapter presents energy-saving approaches and the role of climate factors in the operation of the system. The research work has helped in increasing knowledge in the cold room equipment performance based on conditions and load impacts with potential for improvement in HVAC systems design and controller configuration. However, this study offers a starting point for further work done to enhance the existing systems used in cold room and chamber with the factors influencing the energy efficiency, temperature control and overall operation.

REFERENCES

[1] R. Abdullah and A. M. Rodzi, "Labor utilization and man to machine ratio study at a semiconductor facility," Journal of Engineering and Technology (JET), vol. 2, pp. 75–84, 2011.

[2] Angi, "All the parts of an HVAC system explained," Sep. 19, 2022. [Online]. Available: https://www.angi.com/articles/hvac-system-parts.htm. [Accessed: Jan. 3, 2025].

[3] N. Asim, M. Badiei, M. Mohammad, H. Razali, A. Rajabi, L. C. Haw, and M. J. Ghazali, "Sustainability of heating, ventilation and air-conditioning (HVAC) systems in buildings—An overview," International Journal of Environmental Research and Public Health, vol. 19, no. 2, p. 1016, 2022. doi: 10.3390/ijerph19021016.

[4] S. Barbhuiya, B. B. Das, and M. Idrees, "Thermal energy storage in concrete: A comprehensive review on fundamentals, technology and sustainability," Journal of Building Engineering, vol. 82, p. 108302, 2024. doi: 10.1016/j.jobe.2023.108302.

[5] A. Bhatia, "HVAC design for pharmaceutical facilities," [Online]. Available: https://www.cedengineering.com/userfiles/M05-006%20-%20HVAC%20Design%20for%20Pharmaceutical%20Facilities%20-%20US.pdf. [Accessed: Jan. 3, 2025].

[6] S. Bharati, "Review paper on energy efficiency technologies for heating, ventilation and air conditioning (HVAC)," Holtop, 2017. [Online]. Available: https://www.holtop.com/uploads/Review-Paper-On-Energy-Efficiency-Technologies-For-Heating-Ventilation-And-Air-Conditioning-HVAC.Pdf. [Accessed: Jan. 3, 2025].

[7] L. Cong, Q. Yu, G. Qiao, Y. Li, and Y. Ding, "Effects of an air curtain on the

temperature distribution in refrigerated vehicles under a hot climate condition," Journal of Thermal Science and Engineering Applications, vol. 11, no. 6, 2019. doi: 10.1115/1.4043467.

[8] Danfoss, "Cold storage room 'what you need to know about refrigeration' – part 2," [Online]. Available: https://www.danfoss.com/en/service-and-support/case-stories/dcs/cold-storage-room-what-you-need-to-know-about-refrigeration-part-2/. [Accessed: Jan. 3, 2025].

[9] R. C. Gonzalez and R. E. Woods, Digital Image Processing, 3rd ed., Pearson Education Inc., 2010.

[10] IEEE Xplore, "IEEE Xplore full-text PDF," [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9345700. [Accessed: Jan. 3, 2025].

[11] INTARCON, "Types of cold rooms," Jun. 15, 2022. [Online]. Available: https://www.intarcon.com/en/types-of-cold-rooms/. [Accessed: Jan. 3, 2025].

[12] H. Jouhara and J. Yang, "Energy efficient HVAC systems," Energy and Buildings, vol. 179, pp. 83–85, 2018. doi: 10.1016/j.enbuild.2018.09.001.

[13] S. Mercier, S. Villeneuve, M. Mondor, and I. Uysal, "Time-temperature management along the food cold chain: A review of recent developments," Comprehensive Reviews in Food Science and Food Safety, vol. 16, no. 4, pp. 647–667, 2017. doi: 10.1111/1541-4337.12269.

[14] N. Mukherjee, "The coefficient of performance [COP]: Refrigeration vs. heat pump," LinkedIn, [Online]. Available: https://www.linkedin.com/pulse/what-coefficient-performance-cop-nikhilesh-mukherjee-egrmf. [Accessed: Jan. 3, 2025].

[15] D. S. Naidu and C. Rieger, "Advanced control strategies for heating, ventilation,

air-conditioning, and refrigeration systems—An overview: Part I: Hard control," HVAC&R Research, vol. 17, no. 1, pp. 2–21, 2011. doi: 10.1080/10789669.2011.540942.

[16] M. Nasif, R. AL-Waked, G. Morrison, and M. Behnia, "Membrane heat exchanger in HVAC energy recovery systems, systems energy analysis," Energy and Buildings, vol. 42, no. 10, pp. 1833–1840, 2020. doi: 10.1016/j.enbuild.2020.05.020.

[17] V. N. Kumar, H. V. Gangadharappa, H. C. Kiran, and G. S. H. Gowda, "Temperature mapping study on a cold room used for storage of pharmaceutical products," International Journal of Pharmaceutical Sciences Review and Research, vol. 44, no. 1, pp. 265–274, 2017.

[18] N. Nethaji, T. Mohideen, and M. Nethaji, "Energy conservation in room air conditioner unit by recovering cold energy from condensate," International Journal of Refrigeration, vol. 104, pp. 95–102, 2019. doi: 10.1016/j.ijrefrig.2019.05.005.

[19] H. Nicholas, N. A. Goldschmidt, and U. Thomsen, "Temperature and humidity requirements in pharmaceutical facilities," International Society for Pharmaceutical Engineering (ISPE), 2021. [Online]. Available: https://ispe.org/pharmaceutical-engineering/september-october-2021/temperature-humidity-requirements-pharmaceutical. [Accessed: Jan. 3, 2025].

[20] M. N. Rahman, R. Abdullah, and N. Kamarudin, "Work study techniques evaluation at back-end semiconductor manufacturing," in Proc. 2012 Int. Conf. Design and Concurrent Engineering, Melaka, Malaysia, 2012, vol. 2, pp. 24–27.

[21] F. Sarrafzadeh Javadi and R. Saidur, "Thermodynamic and energy efficiency analysis of a domestic refrigerator using Al2O3 nano-refrigerant," Sustainability, vol. 13, no. 10, p. 5659, 2021. doi: 10.3390/su13105659.

[22] A. Sazanskyi and M. Khmelniuk, "Performance analysis of the refrigeration system for improving energy efficiency," International Science Journal of Engineering & Agriculture, vol. 2, no. 2, pp. 91–102, 2023. doi: 10.46299/j.isjea.20230202.09.

[23] M. Seraj, M. Parvez, O. Khan, and Z. Yahya, "Optimizing smart building energy management systems through industry 4.0: A response surface methodology approach," Green Technologies and Sustainability, vol. 100, p. 100079, 2024. doi: 10.1016/j.grets.2024.100079.

[24] E. K. Simpeh, J.-P. G. Pillay, R. Ndihokubwayo, and D. J. Nalumu, "Improving energy efficiency of HVAC systems in buildings: A review of best practices," International Journal of Building Pathology and Adaptation, vol. 40, no. 2, pp. 165–182, 2021. doi: 10.1108/ijbpa-02-2021-0019.

[25] A. Sularno, F. Soelami, and Y. Bindar, "Experimental and numerical investigation of cooling performance of a cold storage in a pharmaceutical industry," Journal of Physics: Conference Series, vol. 1090, p. 012012, 2018. doi: 10.1088/1742-6596/1090/1/012012.

[26] M. Usman, D. Jonas, and G. Frey, "A methodology for multi-criteria assessment of renewable integrated energy supply options and alternative HVAC systems in a household," Energy and Buildings, vol. 273, p. 112397, 2022. doi: 10.1016/j.enbuild.2022.112397.

[27] S. Bokhorst et al., "Variable temperature effects of Open Top Chambers at polar and alpine sites explained by irradiance and snow depth," Global Change Biology, vol. 19, no. 1, pp. 64–74, 2012. doi: 10.1111/gcb.12028.

[28] J. Karlsson, L. Wadsö, and M. Öberg, "A conceptual model that simulates the influence of thermal inertia in building structures," Energy and Buildings, vol. 60, pp. 146–151, 2013. doi: 10.1016/j.enbuild.2013.01.017.

[29] J. Zhao, Q. Bi, T. Wang, T. Zhang, and F. Feng, "Experimental study on stability and heat transfer characteristics of separated heat pipe with a compressible volume condenser," Case Studies in Thermal Engineering, vol. 64, p. 105511, 2024. doi: 10.1016/j.csite.2024.105511.

[30] O. T. Olaniyan et al., "Evaporative cooling principles: Direct and indirect air cooling, and direct evaporative cooling," Elsevier EBooks, pp. 63–74, 2023. doi: 10.1016/b978-0-323-90039-3.00012-8.

[31] ScienceDirect, "Temperature fluctuation," [Online]. Available: https://www.sciencedirect.com/topics/engineering/temperature-fluctuation. [Accessed: Jan. 3, 2025].

[32] T.-E. Tsai, H.-H. Wu, C.-C. Chang, and S.-L. Chen, "Two-phase closed thermosyphon vapor-chamber system for electronic cooling," International Communications in Heat and Mass Transfer, vol. 37, no. 5, pp. 484–489, 2010. doi: 10.1016/j.icheatmasstransfer.2010.01.010.

[33] J. Dehghani, M. Hosseini, A. Abbasi, and R. Saidur, "Thermal performance and stability analysis of Al2O3 nanofluid based latent heat storage for cooling systems in hot climates," Renewable Energy, vol. 189, pp. 164–176, 2022. doi: 10.1016/j.renene.2022.03.089.

[34] Dibekulu, D. (2020). An overview of data analysis and interpretations in research. ResearchGate. Retrieved from https://www.researchgate.net/publication/365668845_An_Overview_of_Data_Analysis_and_Interpretations_in_Research

[35] Ferreira, T. (2020, May 12). How does result analysis help in decision-making? MyABCM. Retrieved from https://myabcm.com/how-does-result-analysis-help-in-decision-making/

[36] Service, & Service. (2023). How to adjust your HVAC system for fluctuating temperatures. Serviceexperts.ca. Retrieved from https://www.serviceexperts.ca/blog/how-to-adjust-your-hvac-system-for-fluctuating-temperatures/

[37] US EPA. (2014, October 17). Heating, ventilation and air-conditioning systems, part of indoor air quality design tools for schools. US EPA. Retrieved from https://www.epa.gov/iaq-schools/heating-ventilation-and-air-conditioning-systems-part-indoor-air-quality-design-tools

[38] Zhu, S., Dalgo, D., Jelena Srebric, & Kato, S. (2017). Cooling efficiency of a spot-type personalized air-conditioner. Building and Environment, 121(3). https://doi.org/10.1016/j.buildenv.2017.05.007

[39] CHAN, K. C. (2005). Advanced control of condensing temperature for enhancing the operating efficiency of air-cooled chillers. Building and Environment. https://doi.org/105518462/thumbnails/1

[40] Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. Renewable and Sustainable Energy Reviews, 141, 110786. https://doi.org/10.1016/j.rser.2021.1107

[41] Hoyt, T., Arens, E., & Zhang, H. (2015). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment, 88, 89–96. https://doi.org/10.1016/j.buildenv.2014.09.010

[42] Heat Retention - An overview | ScienceDirect Topics. (n.d.). ScienceDirect. Retrieved from https://www.sciencedirect.com/topics/engineering/heat-retention

[43] Alnuaimi, A., Natarajan, S., & Kershaw, T. (2022). The comfort and energy impact of overcooled buildings in warm climates. Energy and Buildings, 260, 111938. https://doi.org/10.1016/j.enbuild.2022.111938

[44] Campos, R., Bastos, E., Gaspar, P. D., & Silva, P. D. (2013). Experimental study and numerical modeling of the thermal performance of cold rooms for storage of meat products. 8th World Conference on Experimental Heat Transfer, Fluid Mechanics, and Thermodynamics (ExHFT-8). Retrieved from https://www.researchgate.net/publication/259184925_Experimental_study_and_numerical_modeling_of_the_thermal_performance_of_cold_rooms_for_storage_of_meat_products

[45] Adams, J., & Mccreery, G. (1983). Detection of inadequate core cooling with core exit thermocouples: LOFT PWR experience. U.S. Nuclear Regulatory Commission. Retrieved from https://www.nrc.gov/docs/ML1303/ML13032A566.pdf

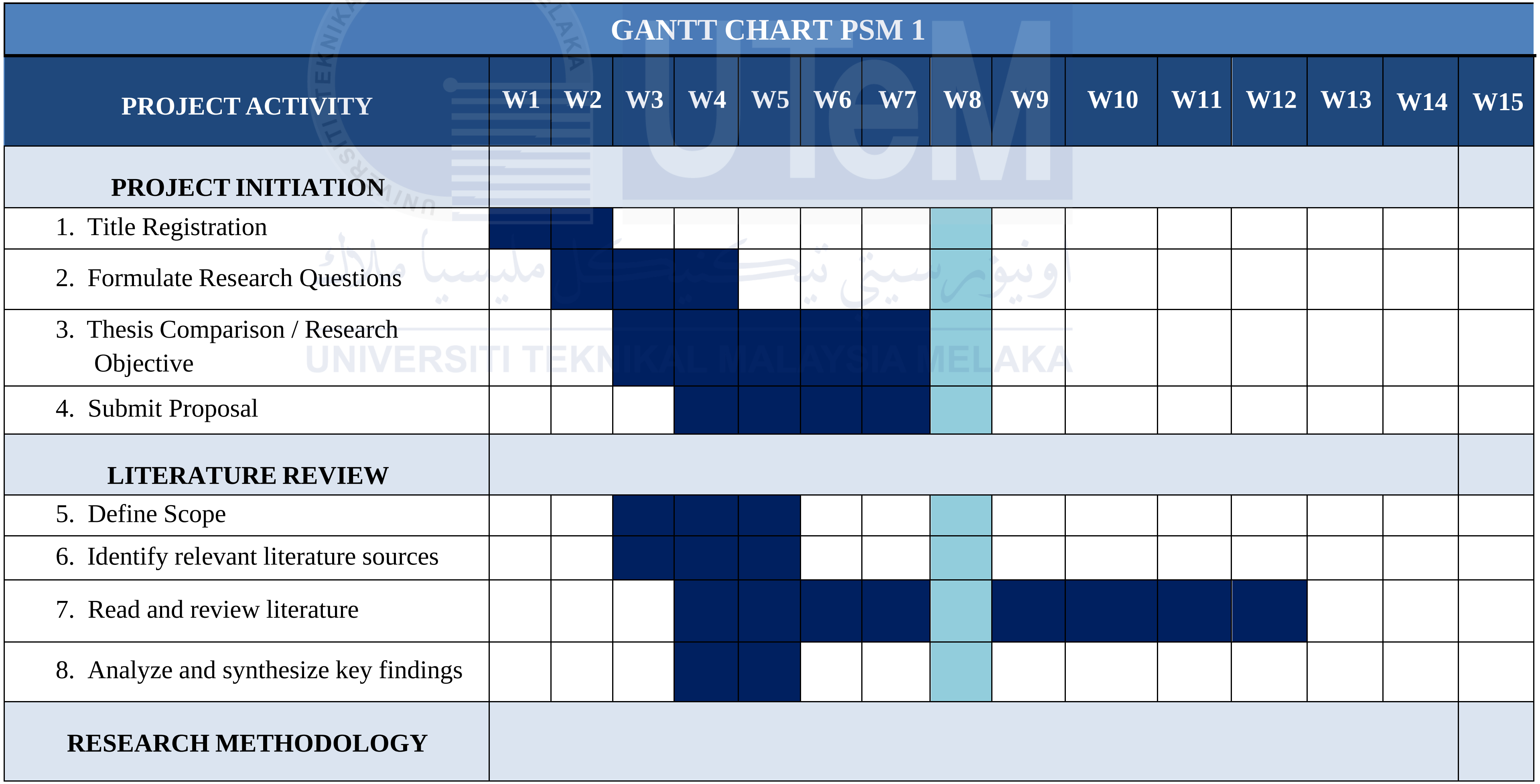
[46] BuildingGreen. (2019). BuildingGreen. Retrieved from https://www.buildinggreen.com/feature/keeping-heat-out-cooling-load-avoidance-strategies/checklist/1

[47] AlWaaly, A. A. Y., Dobson, P. S., Paul, M. C., & Steinmann, P. (2017). Thermocouple heating impact on the temperature measurement of small volume of water in a cooling system. Applied Thermal Engineering, 127, 650–661. https://doi.org/10.1016/j.applthermaleng.2017.08.066

[48] Mishra, A. K., Loomans, M. G. L. C., & Hensen, J. L. M. (2016). Thermal comfort of heterogeneous and dynamic indoor conditions — An overview. Building and Environment, 109, 82–100. https://doi.org/10.1016/j.buildenv.2016.09.016

APPENDICES 1

The Gantt Chart illustrates the project’ schedule for PSM



9. Selection of Appropriate Research Techniques															
10. Evaluate each technique based on feasibility, relevance and suitability															
11. Justify the selection of chosen techniques															
EXPERIMENT DESIGN AND SETUP															
12. Lab Preparation															
13. Identify necessary equipment															
14. List down equipment needed															
15. Consult with experts/supervisors															
16. Review experimental requirements															
17. Locate equipment in respective labs															
18. Map out equipment locations															
19. Coordinate equipment availability and booking															
20. Schedule equipment use															

21. Communicate with lab administrators															
22. Ensure equipment readiness															
23. Inspect equipment condition															
24. Perform maintenance if necessary															
25. Ensure calibration and calibration records are up to date															
REPORTING															
26. Writing Progress Report															
27. Submit Progress Report															
28. Presentation of Progress Report															

- **INDICATES MID SEM BREAK**
- **INDICATES WORK PROGRESS**

APPENDICES 2

The Gantt chart illustrates the project's schedule for PSM 2**.**

GANTT CHART PSM 2															
PROJECT ACTIVITY	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**	**W13**	**W14**	**W15**
LAB TESTING															
1. Set up measuring instruments															
2. Calibrate equipment															
3. Conduct experiments according to plan															
4. Data Collection & Record Data															
5. Ensure accuracy of measurements															
6. Evaluation (Analyze collected data)															
INTERPRETATION OF RESULTS															
7. Analyze data comprehensively															

8. Compare with expected outcomes															
9. Identify trends and patterns															
10. Interpret findings in relation to research objectives															
11. Draw conclusions based on analysis															
12. Validate results with literature and existing knowledge															
REPORTING															
13. Writing Progress Report															
14. Submit Progress Report															
15. Correcting Final Report															
THESIS FINALIZATION															
16. Poster Presentation															
17. Thesis Defense															

- INDICATES MID SEM BREAK

- INDICATES WORK PROGRESS

SV Declaration Form

Form B/PSMFTKM/Rev.01

UTeM

FACULTY OF TECHNOLOGY AND MECHANICAL ENGINEERING
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BACHELOR DEGREE PROJECT
SUPERVISOR DECLARATION FORM

BACHELOR DEGREE PROJECT 1 ☐ **BACHELOR DEGREE PROJECT 2** ☑

SEMESTER 1 **SESSION** 2024 / 2025

A. DETAILS OF STUDENT *(to be completed by student)*

Name : SEELLANN A/L M. GUNAIAGRAN

Program : BMKH Matric No. : B092110475 Phone No. : 016-9581990

Title : COOLING EFFICIENCY: ANALYZING Cooling Rate AND RECOVERY TIMES IN A COLD ROOM LOCATED IN HVAC LABORATORY

B. CHECKLIST *(to be completed by student, choose only 1)*

BACHELOR DEGREE PROJECT 1 *(Please tick (/) if completed)*

Project Proposal ☐ E-log book ☐

BACHELOR DEGREE PROJECT 2 *(Please tick (/) if completed)*

Full report ☑ E-log book ☑ Technical paper ☑

Student's Signature :

Date : 8/1/2025

C. CERTIFICATION BY SUPERVISOR ~~*(to be completed by student, choose only 1)*~~

Comments:

☑ I hereby certified that the student is completed all the documents as stated in Part B and recommended for evaluation

☐ Not recommended for evaluation

Supervisor's Signature And Stamp : TS. MOHD FAEZ BIN ZAINOL
Jurutera Pengajar
Fakulti Teknologi Dan Kejuruteraan Mekanikal
Universiti Teknikal Malaysia Melaka (UTeM)

Date : 8/1/2025

REMINDER:
Kindly submit the completed form to the PSM (JTK) FTKM Committee

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International Standard ISO 5151

Table 1 — Cooling capacity rating conditions

Parameter	Standard rating conditions		
	T1	T2	T3
Temperature of air entering indoor-side:			
— dry-bulb	27 °C	21 °C	29 °C
— wet-bulb	19 °C	15 °C	19 °C
Temperature of air entering outdoor-side:			
— dry-bulb	35 °C	27 °C	46 °C
— wet-bulb[a]	24 °C	19 °C	24 °C
Test frequency[b]	Rated frequency		
Test voltage	See Table 2		

NOTE

T1 Standard cooling capacity rating conditions for moderate climates.

T2 Standard cooling capacity rating conditions for cool climates.

T3 Standard cooling capacity rating conditions for hot climates.

[a] The wet-bulb temperature condition shall only be required when testing air-cooled condensers which evaporate the condensate.

[b] Equipment with dual-rated frequencies shall be tested at each frequency.