DEVELOPMENT OF CAR AIR-CONDITIONING TEST RIG USING AN ELECTRICAL COMPRESSOR

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**A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering Technology (Maintenance Technology) with Honours**

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DECLARATION

I declare that this choose an item, entitled "Development of Car Air-Conditioning Test Rig Using An Electrical Compressor" is the result of my own research except as cited in the references. The choose an item, has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ______________________

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Date : 31/ 12 / 2024

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 (Maintenance Technology) with Honours.

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DEDICATION

This thesis is dedicated to my parents, whose unwavering support, encouragement, and belief in my abilities have been a constant source of inspiration and strength throughout my academic journey. Their sacrifices and guidance have been invaluable, and I am profoundly grateful for their love and patience. To my friends and mentors, who have provided endless support, insightful discussions, and continuous motivation, I extend my deepest appreciation. Your contributions have been instrumental in shaping my academic and personal growth. Finally, I dedicate this work to all those who believe in the power of perseverance, dedication, and hard work. May this thesis serve as a testament to the relentless pursuit of knowledge and the enduring spirit of inquiry. Thank you for being a part of this journey.

ABSTRACT

Test rigs in educational settings have been proven to enhance learning by providing hands-on experience, improving comprehension of complex concepts, and fostering practical skills among students. However, it still lack of studies that covered topic about various types of compressor in automotive HVAC systems. Herein, this research aims to develop a Car Air-Conditioning Electrical Compressor Test Rig (CAECT) to evaluate the performance of system under various operational conditions for laboratory learning. Second objective is to study the relationship of refrigerant condition with different RPM affecting vibration level and temperature on alternative test rig. The development process followed the DoE approach included structural design, integration of monitoring equipment, validation through leak and also functionality testing. Online vibration monitoring was conducted using real-time data acquisition tools to record vibration level. Results shows that the developed test rig achieved a Coefficient of Performance (COP) of 5 and a maximum cooling temperature of 8°C, demonstrating its efficiency for laboratory learning. Meanwhile, data analysis revealed that RPM is the most influential parameter on vibration, with higher RPMs (1000, 1300, 1600, and 1900) increasing the vibrations and compressor temperatures, although it does not affect cooling temperature. Additionally, refrigerant levels significantly impact both cooling and compressor temperatures. The optimal refrigerant level of 320g achieved an 8°C cooling temperature and a minimal compressor temperature of only 39°C in idle RPM. However, refrigerant levels had an inconsistent effect on vibration, leading to fluctuations based on the applied quantity. These development and findings demonstrates the test rig is essential for laboratory learning and for future improvement in automotive and HVAC industry.

ABSTRAK

Pelantar ujian dalam tetapan pendidikan telah terbukti meningkatkan pembelajaran dengan menyediakan pengalaman praktikal, meningkatkan pemahaman konsep yang kompleks, dan memupuk kemahiran praktikal di kalangan pelajar. Walau bagaimanapun, masih kurang kajian yang merangkumi topik tentang pelbagai jenis pemampat dalam sistem HVAC automotif. Di sini, penyelidikan ini bertujuan untuk membangunkan Rig Ujian Pemampat Elektrik Penyaman Udara Kereta (CAECT) untuk menilai prestasi sistem di bawah pelbagai keadaan operasi untuk pembelajaran makmal. Objektif kedua adalah untuk mengkaji hubungan keadaan penyejuk dengan RPM berbeza yang mempengaruhi tahap getaran dan suhu pada pelantar ujian alternatif. Proses pembangunan mengikut pendekatan DoE termasuk reka bentuk struktur, penyepaduan peralatan pemantauan, pengesahan melalui kebocoran dan juga ujian kefungsian. Pemantauan getaran dalam talian telah dijalankan menggunakan alat pemerolehan data masa nyata untuk merekod tahap getaran. Keputusan menunjukkan bahawa pelantar ujian yang dibangunkan mencapai Pekali Prestasi (COP) 5 dan suhu penyejukan maksimum 8°C, menunjukkan kecekapannya untuk pembelajaran makmal. Sementara itu, analisis data mendedahkan bahawa RPM adalah parameter yang paling berpengaruh pada getaran, dengan RPM yang lebih tinggi (1000, 1300, 1600, dan 1900) meningkatkan getaran dan suhu pemampat, walaupun ia tidak menjejaskan suhu penyejukan. Selain itu, paras penyejuk memberi kesan ketara kepada suhu penyejukan dan pemampat. Paras penyejuk optimum 320g mencapai suhu penyejukan 8°C dan suhu pemampat minimum hanya 39°C dalam RPM terbiar. Walau bagaimanapun, paras penyejuk mempunyai kesan yang tidak konsisten terhadap getaran, yang membawa kepada turun naik berdasarkan kuantiti yang digunakan. Perkembangan dan penemuan ini menunjukkan pelantar ujian adalah penting untuk pembelajaran makmal dan untuk penambahbaikan masa depan dalam industri automotif dan HVAC.

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LIST OF SYMBOL AND ABBREVIATION

CAECT	-	Car Air-Conditioning Electrical Compressor Test Rig
HVAC	-	Heating, Ventilation and Air Conditioning
eVTOL	-	electric Vertical Take-Off
PAV	-	Personal Air Vehicle
DAQ	-	Data Acquisition System
LDV	-	Laser Doppler Velocimetry
EV	-	Electrical Vehicle
ANOVA	-	Analysis of Variance
AC	-	Air Conditioning
SUV	-	Sport Utility Vehicles
CoP	-	Coefficient of Performance
CFC	-	Chlorofluorocarbon
CFC-12	-	Dichlorodifluoromethane
ODP	-	Ozone Depletion Potential
GWP	-	Global Warming Potential
BTU	-	British Thermal Unit
UV	-	Ultraviolet
RMS	-	Root Mean Square
DoE	-	Design of Experiment
DC	-	Direct Current
V	-	Voltage
RPM	-	Rate Per Minutes
W	-	Watt
°C	-	Degree Celsius
CO_2	-	Carbon Dioxide
kW	-	Kilo Watt
m/s^2	-	Meter per second square
dB	-	Decibel

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In the educational process, there are three basic types of learning style which are kinesthetics, auditory and visual. Kinesthetics learning is a learning style that takes place by the students carrying out physical activities. For visual learning, a learner needs to see information in order to process it. Approximately 65% of the population are visual learners (Vieira et al., 2018). The concept of these learning styles is the main factor towards the development of the test rig. Teaching and learning aids are tools used by a lecturer or instructors to enhance the learning capability of the students and improve capacity of remembering the concepts. They could be audio or visual aids such as videos or tactile like test rig.

An important benefit from a visual approach to science and engineering is better communication. Visual approaches let scientists and engineers communicate more complex and subtler concepts to each other and to students, and visual approaches to learning can engage the student more fully in the idea (Nurlaela et al., 2018). Based on the above statement, instructors can deal with complex theory topics during lab or class session by using visual approach. Looking to the exact object can help the student on having the idea of the object rather than need to imagine by reading text.

The implementations of these learning styles are not an exception in mechanical industries. The use of test rig are very important and helpful for any training organisation. It can be developed based on various topics of the mechanical maintenance studies. The project that was developed is a set of test rig which pointing on the comparison between electric compressor. Automotive air conditioning systems play a pivotal role in enhancing vehicle comfort, especially in regions experiencing extreme weather conditions. Traditional single compressor systems have been the standard. However, with advancements in technology and increased environmental awareness, the shift toward electrical compressor systems has gained momentum. These systems offer potential improvements in energy efficiency, cooling performance, and reliability.

The significance of studying such systems using a test rig cannot be overstated. A test rig allows for precise control over environmental variables and system parameters, enabling a detailed examination of system behaviour that might not be feasible in on-road tests. This controlled setup helps isolate specific factors influencing system performance, including compressor efficiency, temperature, pressure, and system configuration. Moreover, the environmental impact of automotive air conditioning systems is a growing concern. With global regulations tightening on vehicular emissions and energy consumption, understanding how compressor systems can reduce energy usage and greenhouse gas emissions is paramount. Therefore, in this study electric compressor using scroll type was developed which call Car Air-Conditioning Electrical Compressor Test Rig (CAECT).

1.2 Problem Statement

Currently now an advanced world where technology is always evolving, providing efficient accessible learning opportunities is very important for the educational system. Globalization and digitalization actually impact all sector including education itself. When there's a lack in educational resources or learning aids that includes in the application of technologies in the mechanical industry which is car air conditioning system, it will affect the student's attention and loss of interest in the learning process. Because of that, students are not able to grasp the basic skills when there is less interaction between the instructor and the student.

Next, the automotive and maintenance industry faces a significant gap in the analysis and development related to various types of compressors used in car air conditioning systems (Alkan & Hosoz, 2010). Despite the critical role that compressors play in ensuring optimal cooling performance, there is a lack of comprehensive tools that enable an in-depth understanding and evaluation of different compressor types, such as rotary, scroll, and swash plate compressors specifically in electric compressor.

Lastly, rapid advancement of HVAC and automotive technologies outpacing the current curriculum. As HVAC systems evolve, educational institutions often struggle to update their teaching materials and equipment, leaving students learning from outdated resources. This gap can result in students being underprepared for the workforce, lacking the necessary skills to operate and troubleshoot modern HVAC systems. Based on Andriyani et al. (2020) stated that the advancement of technology make automotive and HVAC industry has to improve rapidly, it causes the training for technicians and students must be update continuously.

1.3 Research Objective

The aims of the project are:-

1) To develop the car air-conditioning electrical compressor test rig for laboratory learning.
2) To study the relationship of different refrigerant condition with different RPM affecting vibration level and temperature.

1.4 Research Scopes

The research scope focused on the comprehensive development of a test rig utilizing the air conditioning system of a Honda Jazz Hybrid 2016 but using electrical compressor. This included designing the framework and ensuring the structural integrity and durability of the test rig. The test rig was built to measure key performance parameters, including compressor pressure, temperature and vibration.

Sensors and measurement devices were integrated into the test rig to monitor the critical parameters stated. This ensured high accuracy and reliability in data collection. Robust sensors and instruments were placed on each basic HVAC component to collect, process, and interpret the data.

Lastly, the test rig served as a practical educational tool for students. An output data of developed test rig is collected to leverage the test rig's capabilities for laboratory learning. For analysis, the alternative test rig which has same operation as CAECT was studied in terms of refrigerant condition with different RPMs affecting vibration levels using online vibration monitoring also with cooling temperature and compressor temperature, this assessing its capability to provide valuable insights into the compressor's and system performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A test rig is an equipment of machinery that is primarily used to test and assess the capability and performance of components for specific use (Nitschke et al., 2019). It Defined as a bespoke research and testing device designed for a specific application. It is a form of hardware prototype built for lab testing and is usually a collection of configurable circuits or modules that demonstrate the key functionality of a new idea or piece of technology. In this chapter will focus on previous research, fundamental theory, definition and basic structure of HVAC system in automotive.

Building test rig devices is beneficial or even essential, the purpose of it is to understanding the benefit of a new process, idea or piece of technology and providing benchmark data to support further development. So in this literature section, it will explain the theoretical and fundamentals in automotive air-conditioning system with support statement and operation related to test rig development and functionality.

2.2 Previous Study on Test Rig Development using Design of Experiment (DoE)

Based on the Bianchini et al. (2015) the test rig that has been already develop is designed to test industrial impellers in an open-loop configuration with ambient inlet conditions. The rig incorporates numerous sensors for dynamic pressure, total pressure, flow velocity, and temperature, allowing comprehensive data collection along the flow path. Additional advanced systems such as fast-response pressure probes and Laser Doppler Velocimetry (LDV) are also supported.

Similarly, a modular design for the air-conditioning compressor test rig will enable testing of different compressor types and configurations, facilitating detailed performance comparisons and component-level optimizations. Test rig by the author used of advanced sensors and measurement devices, such as dynamic pressure sensors and LDV systems, ensures comprehensive data collection and high accuracy. While CAECT also integrating sophisticated sensors to monitor parameters like temperature, pressure, current, and vibration will ensure accurate and reliable data for performance evaluation and optimization. The purpose is to compare and gather data in specific operation.

2.2.1 Application of Design of Experiments (DoE) in Test Rig

Design of experiments is defined as a branch of applied statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters (Bauer et al., 2022). The author study to improve design of experiment about gearbox efficiency modelling using neural networks. The test planning was divided into preliminary and main tests, with measuring points optimally distributed in the characteristic diagram for use in neural networks.

The key components of the author is by use control variables which is speed, torque, oil quantity and oil temperature. The test setup involved using an advanced Road-to-Rig (R2R) vehicle test rig equipped with sensors for precise measurement of speed, torque, and temperature. In the main experiments, author optimized the distribution of measuring points and employed randomization to avoid clustering, ensuring uniform temperature distribution across the test grid. The author then collected data systematically and used neural networks to model the efficiency, employing a fully-connected multilayer perceptron. Finally, they validated their model by comparing it with conventional methods, achieving significantly improved results with reduced statistical dispersion. This rigorous approach exemplifies the effective use of DoE in optimizing test rig design and enhancing experimental outcomes.

2.2.1.1 Design of Experiment Process

The process starts with defining the problem or system to be tested and identifying the factors and levels to be studied. Moreover, it determine the variables and parameters involve that will be studied. Next, experimental design is created to systematically vary the factors. Then, experiments are conducted, and data is collected on the output. This data is analyzed to fit a model, which helps in understanding the effects and interactions of the factors. Finally, the model is used to predict outcomes and optimize the process, ensuring efficient and reliable performance. There are several major method or techniques use in DoE which is Taguchi and Screening test experiments.

2.2.1.2 Screening Test

Screening is the process of discovering, through statistical design of experiments and modeling, those controllable factors or input variables that have a substantive impact on the response or output which is either calculated from a numerical model or observed from a physical process. The purpose of a screening DOE is to minimize the total number of experimental runs by identifying and excluding variables that are not statistically significant. Besides using a fractional factorial design, also can employ the Plackett-Burman Design to screen out variables that have minimal impact on the response.

A full factorial DOE tests every possible combination of independent variables to see their effects on the response variable, providing the most comprehensive information about the process, including main effects and all interactions. However, using a screening DOE means sacrificing some information, particularly about the interactions between variables. The importance of this loss depends on the specific objectives of experiment. The results are analyzed, often using statistical techniques like Analysis of Variance (ANOVA) to determine the significance of each factor. Table 2.1 is example information of screening test which has 20 run planned and 3 factor, from the parameters it will get the information which factor most influence the response variables which is tire braking distance.

Table 2.1 Example test runs for DoE 1 and 2 for one compound in tire braking distance (Salehi et al., 2020)

Run order	Design order	Load (N)	Speed (km/h)	Angle (°)
1	13	55	5.05	0
2	18	55	5.05	15
3	16	55	5.05	15
4	14	55	5.05	30
5	8	75	10	30
6	15	55	5.05	15
7	7	35	10	30
8	3	35	10	0
9	5	35	0.1	30
10	1	35	0.1	0
11	9	35	5.05	15
12	19	55	5.05	15
13	2	75	0.1	0
14	12	55	10	15
15	20	55	5.05	15
16	10	75	5.05	15
17	17	55	5.05	15
18	11	55	0.1	15
19	6	75	0.1	30
20	4	75	10	0

2.2.1.3 Taguchi Array

Taguchi method, is a statistical approach developed by Genichi Taguchi for improving the quality and performance of products through efficient experimental design. Central to this method is the use of orthogonal arrays, which enable the systematic investigation of multiple factors with a minimal number of experiments. To use a Taguchi array, one begins by clearly defining the problem and objectives of the experiment. The next step is to identify the factors (independent variables) and their respective levels (settings) that could influence the outcome. After this, an appropriate orthogonal array is selected based on the number of factors and levels.

Experiments are conducted according to the combinations specified in the array, and the results are analyzed, it same as with screening test which involve a specific number of test and have high factors with level number, often using statistical techniques like Analysis of Variance (ANOVA) to determine the significance of each factor (Thakre et al., 2022). The analysis helps identify the optimal levels for each factor that yield the best outcome. Finally, confirmatory experiments are performed to verify that the identified optimal conditions lead to the desired improvement. This method is highly efficient, reducing the number of experiments needed and thereby saving time and resources while ensuring high-quality results.

2.2.2 Functionality Testing in Test Rigs

Functionality testing is a critical component of test rig development, ensuring that the system operates as intended under various conditions. Various researchers have conducted functionality tests to validate their test rigs. In the study by Mitra et al. (2016) the functionality testing of an automotive suspension system using a quarter car test rig was shows to simulate real-world conditions and assess the impact of various parameters such as tire pressure, damping coefficient, spring stiffness, sprung mass, camber, toe, and wheel speed on ride comfort and road holding. The functionality tests involved varying these parameters systematically and measuring the resulting ride comfort and road holding. The data collected was then analyzed using statistical methods to optimize the suspension system for improved performance.

Similarly, in the research conducted by Lee et al. (2020) functionality testing was performed during the conceptual design phase of an electric Vertical Takeoff and Landing (eVTOL) Personal Air Vehicle (PAV). The test rig for the eVTOL PAV was used to evaluate the performance of different configurations under various operating conditions. The study employed Design of Experiments (DoE) to systematically vary design parameters and assess their impact on the vehicle's performance. Functionality tests focused on critical factors such as vertical takeoff and landing capabilities, energy consumption, and cruising efficiency. As shows in Table 2.2 is the parameter involve. The results and parameters were used to optimize the design and ensure the vehicle met the desired performance criteria.

Table 2.2 Example of design parameter in eVTOL PAV test rig (Lee et al., 2020)

Design Parameter	Min. Value	Max. Value	Standard Value	Unit
Range	40	50	45	mile
Max speed	110	130	120	kt
Cruise speed	100	120	110	kt
Cruise altitude	5000	10,000	7500	ft
Passengers	1	3	2	PAX
Baggage	40	120	80	lb
Rate of climb	500	1000	750	ft/min
Stall speed	36	40	38	kt
Service ceiling	10,000	15,000	12,500	ft
Turn speed	60	90	75	kt

Identified parameters is important in the functionality testing of a Car Air-Conditioning Compressor Test Rig, as they directly impact the system's performance and reliability. Key parameters such as compressor pressure, temperature, vibration levels and power consumption must be carefully monitored and controlled. By systematically testing these parameters, researchers can fine-tune the system, identify optimal settings, and improve performance.

2.3 Automotive Air conditioning System in Fuel Car Compared to Electric Vehicle Car

EV air-conditioning systems and conventional internal combustion engine vehicle air-conditioning systems have distinct operational requirements and constraints. In EVs, the air-conditioning system plays a critical role in managing the thermal regulation of the battery, which is essential for maintaining vehicle range and battery health. EV air-conditioning systems often include additional components like a second evaporator for battery cooling and more complex control mechanisms to manage multiple heat sources and sinks. Compressors in EVs have its own built-in electric motor, an inverter that converts direct current drawn from the battery into AC, and a separator that separates the compressor oil from the refrigerant. Among the advantages of the solution, where the compressor is powered directly from the battery, is the ability to run the air conditioner while parked, with the engine off.

In conventional vehicles, the air conditioning system is powered by the engine. The system typically uses a belt-driven compressor that is directly connected to the engine, meaning the energy for cooling comes from burning fuel. Conventional systems are primarily designed for cabin cooling. They are generally less complex and focus solely on passenger comfort, without the need for battery thermal management. Also, it affect fuel efficiency, the impact is The most crucial is that both air conditioning system has same 4 basic cycle of refrigerant.

2.4 Refrigerant Cycle in Automotive

EV and fuel cars (internal combustion engine vehicles) use the same basic refrigeration cycle for air conditioning systems. This cycle consists of four main stages which is evaporation, compression, condensation, and expansion (Göltz & Sawodny, 2023).

A refrigerant is a substance used in cooling systems such as air conditioners, refrigerators, and heat pumps to absorb heat and transfer heat through phase changes between liquid and gas states. The primary function of a refrigerant is to facilitate the cooling process by absorbing heat during evaporation and releasing it during condensation. Traditionally, refrigerants such as R-134a (tetrafluoroethene) have been widely used due to their efficiency in transferring heat through phase changes. In these systems, the refrigerant cycles through the air conditioning components, absorbing heat from the car's cabin as it evaporates in the evaporator coil and releasing it outside as it condenses in the condenser coil. The compressor, typically belt-driven by the engine, pressurizes the refrigerant, facilitating these phase changes.

2.4.1 Compressor and Condenser

Refrigeration compressors are typically assessed using both the first and second laws of thermodynamics. The second law of thermodynamics establishes the concept of energy quality, and it can be utilized to evaluate the degradation of energy quality that occurs during a process or cycle (Arqam et al., 2024). Compressor's primary function is to compress the refrigerant gas, increasing its pressure and temperature. When the refrigerant enters the compressor as a low-pressure gas from the evaporator, it is compressed into a high-pressure, high-temperature gas.

Referring to Figure 2.1 the high-pressure gas is then pushed out of the compressor and flows into the condenser. This movement is driven by the compressor's action, ensuring a continuous cycle of refrigerant through the system. In the condenser, the high-pressure gas releases its heat to the surroundings and condenses into a high-pressure liquid. The ambient air flowing over the condenser coils facilitates this heat exchange. Both components are used to release heating air into outside of the car.

2.4.2 Expansion Valve and Evaporator

Referring to the Figure 2.1 the high-pressure liquid refrigerant then passes through an expansion valve or orifice tube, where it undergoes a pressure drop and begins to evaporate. This phase change cools the refrigerant significantly, allowing it to absorb heat when it enters the evaporator. As the low-pressure, cool refrigerant flows through the evaporator, it absorbs heat from the car's cabin air. This process cools the air, which is then blown into the cabin by the blower fan. The now warm, low-pressure refrigerant returns to the compressor, and the cycle repeats. This continuous process ensures that the car's interior remains cool and comfortable.

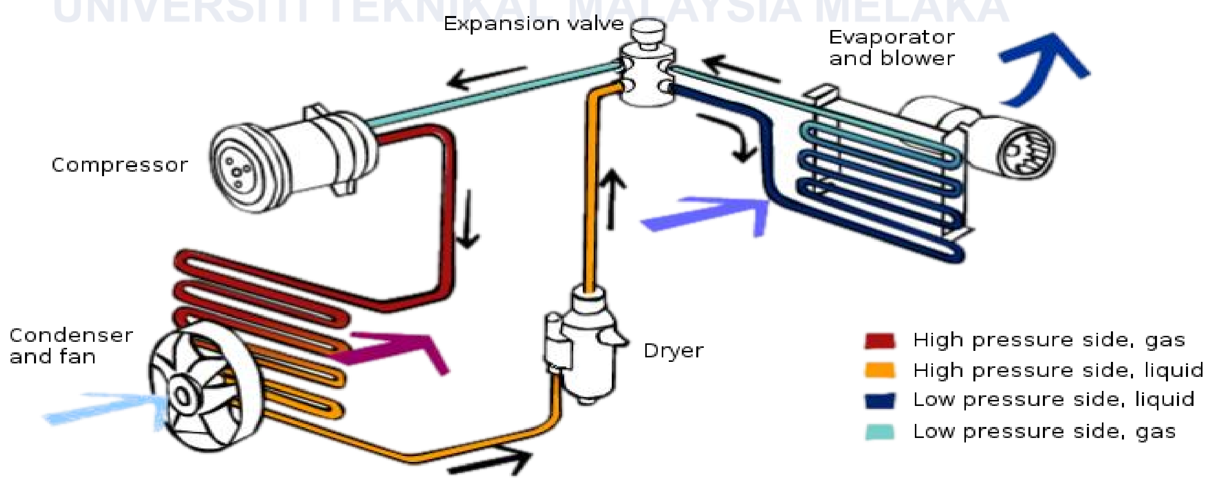


Figure 2.1 Process of refrigerent cycle in automotive system (Arqam et al., 2024)

2.5 Common Types of Compressor in Convention Car

Typically, according to Bhatia (2017) cars use a so-called rotary or scroll compressor that is driven by the motor via a belt. A single serpentine belt drive or several belt drives connected to the engine crankshaft power compressors. When a belt has a large distance between pulleys, a small idler pulley is typically used in conjunction with a belt adjusting device to absorb vibrations from the belt.

2.5.1 Scroll Compressor

Referring to the Figure 2.2 a Scroll Compressor is a spirally wound, fixed scroll and movable scroll that form a pair. The housing and fixed scroll are combined. The moveable spiral can oscillate or orbit without turning completely. A concentric bearing connects the input shaft to the movable scroll. A number of pockets form in between the fixed spiral and the mobile spiral as it oscillates within it. The refrigerant is squeezed as these pockets get smaller, the pressure rises, and it is released through a reed valve at the discharge port in the compressor's rear part.

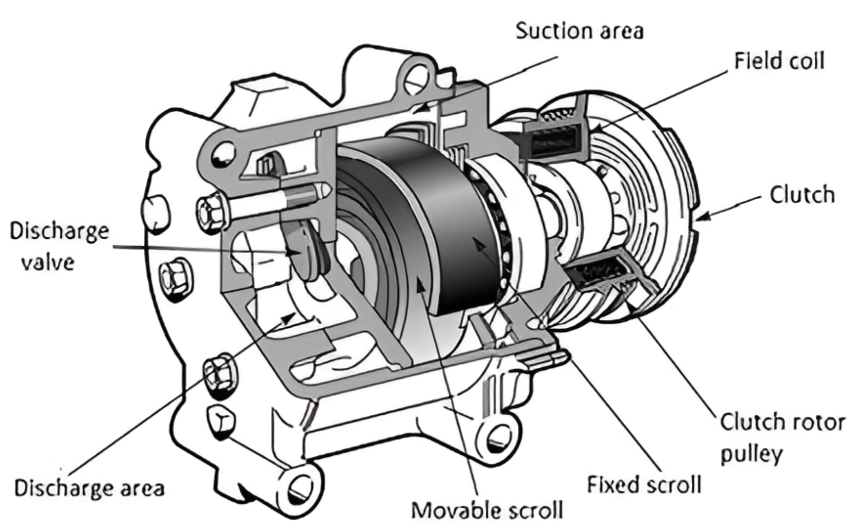


Figure 2.2 Scroll compressor design (Bhatia, 2017)

2.5.2 Rotary Compressor

Rotary compressors physical design varies widely. Both single- and multiple-rotor construction are used. The design of the rotor is the main item that distinguishes the different types of rotary compressors. do not use valves to move the gas through the machine. The advantages is lighter in weight, experience less vibration and do not require heavy foundation (Maurice Stewart, 2019).

2.5.2.1 Vane Type Compressor

The operating principle for a vane compressor is the same as for many compressed air expansion motors which rotary compressor. Referring to the Figure 2.3 The majority of vane compressors are oil-lubricated, and the vanes are often made of unique cast alloys. Within a stator housing, a rotor with radial, movable blade-shaped vanes is eccentrically placed. Centrifugal force pushes the vanes up against the stator walls as it rotates. As the distance between the rotor and stator grows, air is pulled in. The air is captured in the different compressor pockets, which decrease in volume with rotation. The air is discharged when the vanes pass the outlet port.

2.5.3 Swash Plate Compressor

Compressors of the swash-plate or "wobble plate" type are the most widely used for engine-driven mobile air conditioning systems. These cause the pistons to move smoothly back and forth while the shaft rotates. Compared to a reciprocating compressor with two pistons, this design allows for more pulses each revolution. Typically, these compressors have six or 10 pistons. An opposing axial compressor's pistons are joined by a solid component that maintains their predetermined separation from one another. (Maurice Stewart, 2019)

2.5.3.1 Fixed Swash Plates

Fixed swash plate compressors maintain a steady compression ratio and refrigerant discharge rate as the engine rotates. Anti-rotation gears hold the swash plate at a fixed angle, while a cam rotates behind it. The revolving cam and stationary swash plate force the pistons to travel in a plane parallel to the compressor driving shaft. These compressors normally have six or 10 pistons. The pistons in an opposed axial compressor are joined together by a solid component that keeps them at a constant distance from each other.

2.5.3.2 Variable Swash Plate

The swash plate is mounted on a shaft within the compressor, and its angle can be adjusted to vary the piston stroke length. As the swash plate rotates, its angle determines how far the pistons move during each cycle (Wang et al., 2021). When the angle of the swash plate is steep, the pistons have a longer stroke, compressing more refrigerant and increasing the cooling capacity. Conversely, a shallow angle results in a shorter piston stroke, reducing the amount of refrigerant compressed and decreasing the cooling capacity. This variability allows the compressor to adjust its displacement dynamically, matching the cooling demand and optimizing efficiency. By only working as hard as necessary, the compressor reduces fuel consumption and engine load, leading to improved overall vehicle performance and durability.

2.6 Air Conditioning Compressor Failures and Troubleshooting

The most common cause of compressor failures is a loss of lubrication, which can be brought on by leaks, inadequate servicing, low refrigerant levels in the system, obstructions (like clogged orifice tubes that stop oil and refrigerant from flowing to the compressor), and improper service. The car's AC compressor is one of the most important components in a vehicle's air conditioning system. So if it fails, the entire system will not work.

2.6.1 Refrigerant Problems

Refrigerant issues, such as insufficient refrigerant levels due to leaks or overcharging, can lead to compressor failure. Low refrigerant levels cause the compressor to overheat as it struggles to maintain cooling capacity, while overcharging can allow liquid refrigerant to enter the compressor, causing internal damage. To troubleshoot, check refrigerant levels using appropriate gauges to ensure they are within the manufacturer's recommended range. Use a leak detector to identify any refrigerant leaks and repair them promptly. Properly recharging the system with the correct amount of refrigerant is essential to prevent these problems and ensure the system's efficiency and longevity.

2.6.2 Electrical Issues

Electrical problems are a common cause of air conditioning compressor failures, stemming from faulty wiring, blown fuses, or malfunctioning capacitors. These issues disrupt the electrical circuit essential for the compressor's operation, leading to intermittent or complete failure. To troubleshoot electrical problems, start by inspecting all electrical connections for signs of wear, corrosion, or damage. Testing the capacitors and fuses with a multimeter can identify faults, and replacing any defective components is crucial. Ensuring that the wiring is properly insulated and secured helps prevent future electrical issues, thereby maintaining the compressor's reliable operation.

2.6.3 Suction and Discharge Pressure Issues

Incorrect suction or discharge pressures can indicate problems such as blockages, leaks, or incorrect refrigerant charge, all of which can lead to compressor failure. To troubleshoot pressure issues, use gauges to measure the suction and discharge pressures and compare the readings to the manufacturer’s specifications. Identify and correct any discrepancies by checking for blockages, leaks, or incorrect refrigerant levels. Ensuring that the pressures are within the recommended range helps maintain the compressor's efficiency and prevent potential failures.

2.7 Automotive Climate Control System

The cabin of a typical air conditioning system is heated or cooled based on the regulator's setting. It is basically a manual control system for the fan's speed and the temperature of the air blasted into the cabin. The condenser, compressor, evaporator, and heater in climate control systems function in the same fundamental ways as those in manually operated systems (Nielsen et al., 2016). The primary distinction is that it keeps the car operating at a predetermined, manually-selected temperature either heating or cooling.

The climate control system has the advantage of eliminating the requirement for the driver to constantly be distracted from driving in order to alter the climate equipment. The electronics take measurements and based on the original setting, turn on or off the appropriate system (heating/cooling).

Figure 2.3 Climate Control on Car

Referring to the Figure 2.3 is the usual system of blowing and heating the passenger compartment has an A/C button and two controls. One shows the fan speed levels (scale 1, 2, 3, and so on), and the other shows a blue, red scale (cold/hot air). The second knob adjusts the position of the heater damper. The driver sets the temperature and the speed to control the amount of cold air.

2.7.1 Zone Control

The climate control system in cars is single-zone by default. This implies that there is only one temperature set throughout the entire cabin. Different people may experience varying degrees of comfort from this, some may find the car to be quite cold, while others may start to perspire. Every region inside the designated zones is equipped with a distinct sensor that measures the current temperature just in that area (Suroto et al., 2022). After reading the inputs, the temperature control system will adjust the fan speed and engage/disengage. The compressor, which regulates the airflow's intensity and guarantees a suitable combination of hot and cold air.

2.7.2 Dual Zone Climate Control

This has two temperature controls, allowing the car's left and right sides to have separate temperature settings. Additionally, there will be two controllers that allow for separate temperature settings one either side of the dashboard. Certain cars include systems that restrict the temperature differential between the two sides. With this option, you can guarantee a comfortable stay that meets your demands as well as those of the car's owner or driver.

2.7.3 Three-Zone Climate Control

Each of the three zones of climate control has its own temperature controller. The third zone is located in the back seating area, with the first two zones being in the front (left and right). Backseat passengers have control over the temperature and air vent settings, so they can select what's ideal for them.

2.7.4 Four-Zone Climate Control

Each of the four primary seats in an automobile has its own temperature zone. High-end luxury vehicles, mostly limousines like the Mercedes S-Class and other pricey SUVs, have this kind of climate control. But a four-zone climate control, similar to three-zone systems, will enable the driver to regulate the cabin's temperature in the back. Additionally, the 'SYNC' button on these systems lets to set a consistent temperature throughout the vehicle. Additionally, smooth blowing is supplied via the ceiling and door pillar ducts for more cooling and heating comfort.

Figure 2.4 Airflow direction in vehicle (Hadi et al., 2022)

Based on the Figure 2.4 the author stated proper airflow ensures good visibility from the car, defrosts the windows in winter and prevents fogging throughout the year.

2.8 Refrigerant 12, 134a and 1234yf Properties

R12 and R134a are both refrigerants used in recent automotive air conditioning and refrigeration systems, but it differ significantly in the environmental impact and chemical properties. According to Nagalakshmi & Yadav (2014) that COP of R12 is little greater than COP of R134a. Even though COP of R12 is greater than R134a it must be replaced with R134a because of is non-toxic and does not flare up within the whole range of operational temperatures. R12, also known as dichlorodifluoromethane (CFC-12), is a chlorofluorocarbon (CFC) while R134a is a hydrofluorocarbon (HFC) refrigerant developed as an environmentally friendly alternative to R12. Because of this another refrigerant was created, which is R1234yf that has similar properties to R134a but more suitable for environment.

Table 2.3 Properties of R1234yf and R134a (Ashwini, 2018)

Property	R1234yf	R134a
Chemical Formula	$C_4H_2\ F_4$	$C_2H_2\ F_4$
Ozone Depletion Potential (ODP)	0.0	0.0
Global Warming Potential (GWP)	4	1,430
Boiling Point	-29.4°C	-26.1°C
Toxicity	Non-toxic	Non-toxic
Flammability	Mildly flammable	Non-flammable
Lubrication Oil	Synthetic PAG oil	Synthetic ester oil
Application	Automotive AC, refrigeration	Automotive AC, refrigeration
Environmental Impact	Ultra-low GWP, low ODP, future standard	Low ODP, moderate GWP, current standard
Price	Expensive	Non-Expensive

Referring to the Table 2.3, R1234yf is mildly flammable, non-toxic, and environmentally friendly, with zero ODP and a much lower GWP than R134a, making it the preferred choice for modern automotive AC systems. It uses synthetic PAG oil for lubrication. In contrast, R134a, though non-toxic and non-flammable with zero ODP, has a higher GWP and requires synthetic ester oil, making it less sustainable than R1234yf. However, R134a serves as a more economically friendly alternative and mostly used nowadays.

2.9 Modern Automotive HVAC Sensor Operation

Automatic sensor in recent vehicle is widely used for increasing comfort level. The requirement is largely based on the interior and exterior conditions, HVAC system parameters, cabin volume, and number of passengers. Sensor technology is not only become an essential part to monitor the production processes in manufacturing industry but is also used to ensure the smooth functioning of sub-systems by continuously monitoring vehicle dynamics in automotive industry (Soy & Toy, 2021).

2.9.1 Sun Load Sensor

Figure 2.5 Internal photo diode cells

Referring to the Figure 2.5 is the sun load sensor, a photochemical diode attached on the dashboard, sends signals to the climate control module to adjust cooling based on sunlight intensity. Increased sunlight causes the blend door to open and the blower to speed up, while reduced sunlight decreases blower speed and cooling effort.

2.9.2 Humidity Sensors

Next, Generally in Figure 2.6 it is capacitance sensors that measure air moisture to regulate airflow on windows and maintain cabin humidity, enhancing comfort. Typically mounted at the rear-view mirror base.

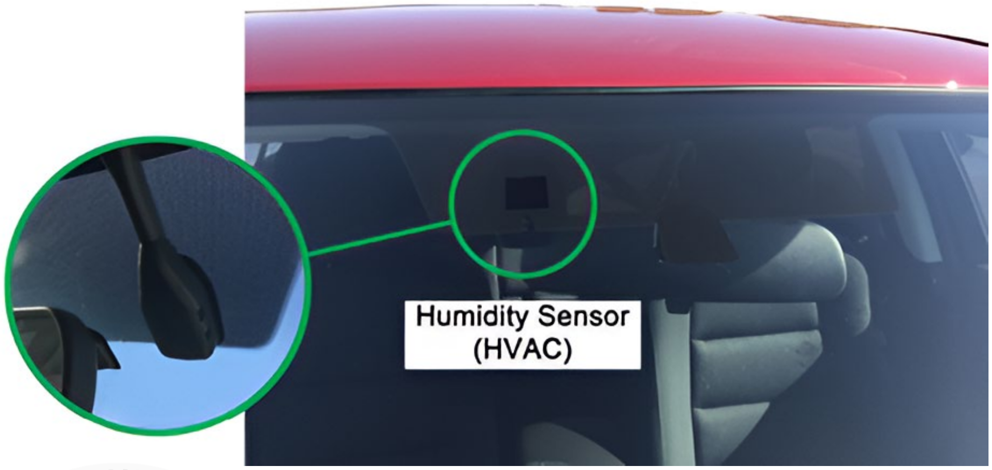


Figure 2.6 Humidity sensor located

2.9.3 Air Quality Sensors

When driving through tunnels, through crowded locations, or while sitting in heavy traffic, air quality sensors can keep bad scents and hazardous gasses out of the cabin. When undesired substances are discovered, the sensor sends a signal to close the ventilation flap or fresh air inlet door. Usually, located behind the grill.

2.9.4 CO_2 Sensors

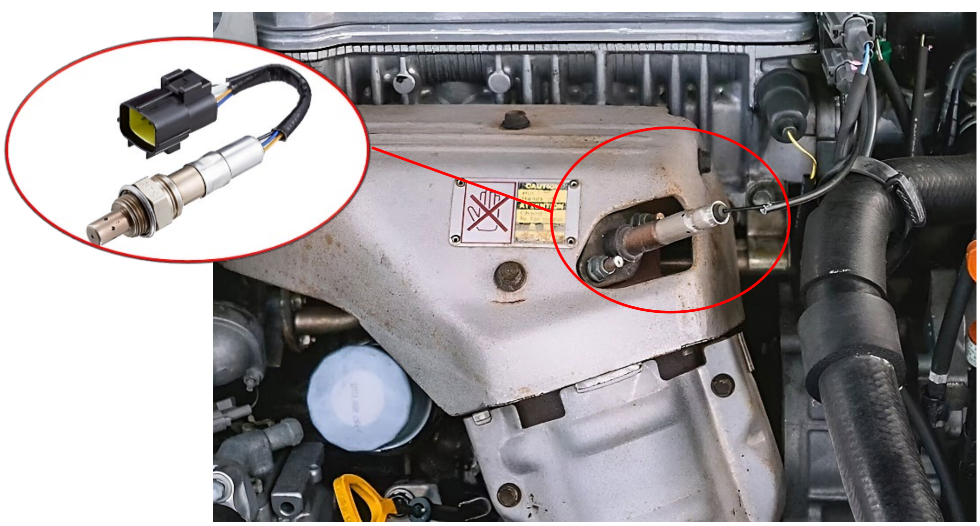


Figure 2.7 CO_2 sensor located

This sensors as in Figure 2.7 is critical for human safety because it monitors cabin air quality by measuring CO_2 levels, which can cause drowsiness. It signals the HVAC system to introduce fresh air when CO_2 exceeds safe levels.

2.9.5 Windscreen Fogging Sensor

Fog is one of the most common HVAC complaints from users and can impair a driver's eyesight. An integrated humidity and temperature sensor in an autonomous fog control system employs a controller to determine the air's dewpoint temperature. Based on the dewpoint temperature, the control unit detects moisture and condensation and modifies the dry air and heating on the windshield.

2.10 Related Performance Evaluation and Diagnostic Techniques in HVAC system

Performance evaluation and diagnostic techniques are essential for ensuring the efficiency, reliability, and longevity of HVAC systems in car. These techniques help in identifying potential issues, optimizing performance, and ensuring that the system operates within the desired parameters.

2.10.1 Cooling Capacity

Cooling capacity of automotive air conditioning systems is an important performance metric that indicates the amount of heat a compressor can remove from the vehicle cabin within a specified period. This capacity is typically measured in kilowatts (kW) or British Thermal Units per hour (BTU/h) and plays a vital role in maintaining passenger comfort and ensuring the efficiency of the air conditioning system, especially under high thermal load conditions such as hot weather.

Based on the Banakar et al. (2014) conducting an experiment cooling capacity for vehicle stated the tests are typically conducted at different ambient temperatures (e.g., 25°C and 35°C) to reflect real-world scenarios. For instance, a vehicle air conditioning system might show a cooling capacity of 4 kW at 900 rpm, consuming 1.2 kW of power. At 2500 rpm, the system might exhibit a cooling capacity of 4.6 kW, consuming 2 kW of power. So, the author use a compressor to test a different cooling capacity in a different speed while my research analysis use different amount of refrigerent to see result on power consumption and vibration level that affecting cooling capacity or not.

2.10.2 Refrigerant Leak Testing

On a 27°C day, the low-pressure gauge of an A/C system should read about 56 psi or higher if the refrigerant charge is adequate. On a 32°C day, the low-pressure reading should be about 70 psi or higher. If the reading is lower, the system likely needs more refrigerant. The actual pressure readings may vary based on the type of refrigerant used (Fonseca & Teodoro, 2019). Referring to the Figure 2.8 is most common leaks area and the highest part that may faulty is condensers (Zhang et al., 2023).

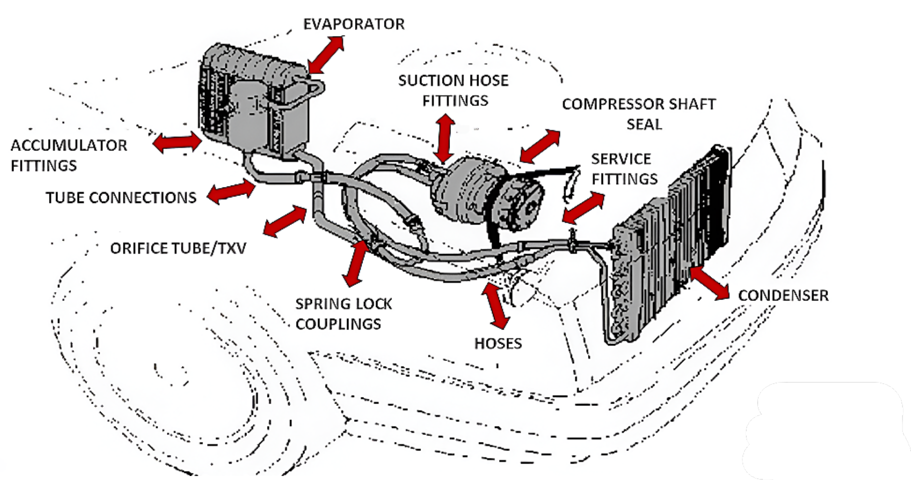


Figure 2.8 Common leaking area in car air-conditioning system (Bhatia, 2017)

2.10.2.1 Ultraviolet (UV) and Dye Leak Detection

This is the common test which is to illuminate dye that has been injected into the system. This may be the best way to find some small leaks that occur only during special circumstances, such as driving vibrations, road shock, or flexing of components and lines. A fluorescent-colored dye is pumped into the A/C system and allowed to circulate, after which a specially designed UV lamp is passed over each component in the A/C system. Referring to the Figure 2.9 if a leak is evident, the coloured dye glows brightly. This method is exceptionally good for pinpointing a small leak. A standard dye application is ¼ fluid ounces.

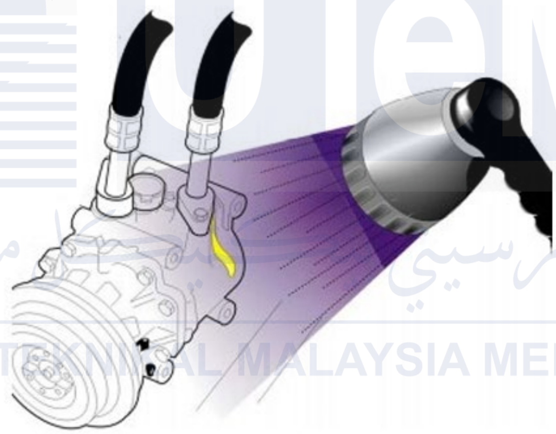


Figure 2.9 UV Fluorescent System (Bryan, 2022)

2.10.2.2 Electronic Leak Detection

There are several methods that Electronic Leak Detectors (ELD) function as refer to Figure 2.10. A faint beeping sound is heard when the unit is turned on, and the ticking sound becomes louder as soon as the probe finds a leak. To do this, slowly move the detecting tip at a distance of around 5 mm along the bottom of the parts and fittings. A false reading or damage to the sensing tip may result by allowing it to come into contact with parts or fittings.

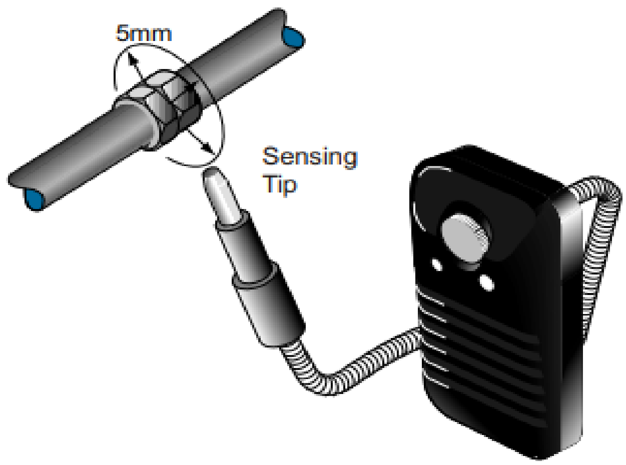


Figure 2.10 Electronic leak detector (Bryan, 2022)

2.10.3 Vibration Signals Analysis on HVAC System

Vibration analysis technique involves placing vibration sensors or accelerometers on key HVAC components like compressors, fans, and motors to monitor real-time vibration data. The study by Nawrocki et al. (2023) focuses on using vibro-acoustic signals to diagnose wear in the spindle bearings of numerical machine tools in the automotive industry. This diagnostic approach is vital for maintaining efficient production processes by ensuring the correct and safe operation of machinery. The researchers analyzed vibration signals, particularly the acceleration, enveloped acceleration, and root mean square (RMS) of vibrations, to set warning and alarm thresholds for spindle bearing wear.

The experiment was conducted on a four-axis machining center, specifically analyzing the spindle bearings using a Schaeffler ProLink and FAG SmartCheck sensors. The analysis showed that significant spikes in vibration levels were linked to failure. It concluded that vibro-acoustic signal analysis is effective for early detection of spindle bearing wear, allowing for timely maintenance and avoiding severe machine failures.

2.11 Summary of Previous Research

Table 2.4 Summary of previous research findings

No.	Author	Title	Method / Description	Strength	Weakness
1.	(Thakre et al., 2022)	Performance optimization of the disc brake system of electric Two-wheeler using Taguchi approach	Taguchi method and for optimizing disc brake performance parameter.	Effective in identifying key factors affecting brake performance, minimizing brake fade and accidents.	Limited scope focuses on electric two-wheelers and specific test rig parameters.
2.	(Mitra et al., 2016)	Design of Experiments For Optimization Of Automotive Suspension System Using Quarter Car Test Rig	Fractional factorial design to optimize suspension parameters for ride comfort and road holding.	High reliability and predictability of the model with R-sq values of 97.70% and 97.99% respectively.	Limited real-world applicability due to reliance on test rigs and theoretical models.
3.	(Salehi et al., 2020)	Parameter optimization for a laboratory friction tester to predict tire ABS braking distance using design of experiments	Design of Experiments (DoE) methodology to derive a mathematical model for predicting tire friction using a LAT100 tester.	Effective in identifying the mutual interactions of factors on tire friction, ensuring accurate predictions for ABS braking distances.	Complex setup and analysis, requiring specialized equipment and knowledge. Limited to laboratory conditions.

No.	Author	Title	Method Use / Description	Strength	Weakness
4.	(Bauer et al., 2022)	Improved design of experiments method for machine-learning-based modelling of gearbox efficiency in a test rig environment	Improved design of experiments method for neural networks to model gearbox efficiency. This involves optimized experimental design, preliminary tests, and main tests with a high density of measuring points.	The method provides better results than conventional approaches. The use of neural networks allows for a continuous and efficient description of gearbox efficiency.	Requires a large amount of experimental data, which can be time-consuming and resource-intensive to collect. The initial setup and optimization process is complex.
5.	(Bianchini et al., 2015)	Development of a research test rig for advanced analyses in centrifugal compressors	Design and development of a new research test rig for centrifugal compressors, focusing on advanced analyses like rotating stall and operating conditions close to the minimum flow limit	The modular design allows testing various stage configurations, enabling systematic optimization of components. It can test industrial impellers at high peripheral Mach number.	The rig operates in an open-loop configuration, which might not fully replicate all industrial conditions.

No.	Author	Title	Method Use / Description	Strength	Weakness
6.	(Lee et al., 2020)	Optimal Design and Design Parameter Sensitivity Analyses of an eVTOL PAV in the Conceptual Design Phase	Design of experiments method used to optimize the design of an electric vertical takeoff and landing personal air vehicle (eVTOL PAV), including screening tests and response surface methodology.	Effective in identifying sensitive design parameters and optimizing multiple design goals concurrently. Uses a comprehensive and systematic approach for early-stage design optimization.	Requires significant computational resources and detailed data for accurate modeling. Initial setup is complex and time-consuming.
7.	(Luiz Caleffo Piva Bigão et al., 2024)	Use of statistical design of experiments (DoE) in Forensic Analysis: A tailored review	Review of the application of DoE and Response Surface Methodology (RSM) in forensic analysis, focusing on sample preparation and the chromatographic and detection phases.	Highlights the effectiveness of DoE/RSM in optimizing analytical methods, reducing analysis time, and minimizing sample and reagent use.	Limited focus on the chromatographic and detection phases. Most studies reviewed used DoE/RSM primarily for sample preparation.

No.	Author	Title	Method Use / Description	Strength	Weakness
8.	(Nitschke et al., 2019)	An advanced experimental method and test rig concept for investigating the dynamic blade-tip/casing interactions under engine-like mechanical conditions	Design and development of a test rig to simulate and analyze the interactions between rotor blades and casing under engine-like conditions.	Provides a detailed and controlled environment for studying blade-tip interactions, enabling optimization and validation of blade and casing designs.	Limited real-world applicability as some phenomena may not be fully replicable in a test rig. Method to interpret data on the test not suitable.
9.	(Nawrocki et al., 2023)	Application of the vibro-acoustic signal to evaluate wear in the spindle bearings of machining centres. In-service diagnostics in the automotive industry	Use of vibro-acoustic signal analysis to monitor and diagnose the wear of spindle bearings in machining centers, focusing on parameters like vibration acceleration, velocity, and envelope.	Enables early detection of wear and potential failure in spindle bearings, improving maintenance and reducing unplanned downtime. Applicable in mass production settings for consistent monitoring.	Requires specialized equipment and knowledge for signal analysis. Initial setup and determination of warning thresholds can be time-intensive.

No.	Author	Title	Method Use / Description	Strength	Weakness
10.	(Andriyani et al., 2020)	Needs analysis of contextual training for automotive technicians	Qualitative approach using interviews with technicians and instructors, and literature review to develop a needs analysis method for effective training in the automotive industry.	Provides a method for needs analysis tailored to the rapid technological advancements in the automotive industry, ensuring relevant and effective training programs.	Limited to the automotive industry in Indonesia only, may not be directly applicable to other industries or regions.
11.	(Soy & Toy, 2021)	Design and implementation of smart pressure sensor for automotive applications	Proposed a low-cost piezoresistive sensing method based smart pressure sensor combining signal conditioning, analog/digital signal processing, and communication circuitry.	Improved reliability and greater accuracy due to built-in temperature compensation, filtering, and self-calibration capabilities. Tested for robustness in dynamic conditions.	Complex initial setup and calibration process. Limited real-world applicability as the design and testing were specific to laboratory and controlled environments.

2.12 Summary of Research Gap

The existing literature on automotive HVAC systems in recent technology give a lot of information, providing detailed insights into various components and performance metrics. Studies such as those by Banakar et al. (2014) offer comprehensive performance evaluations using advanced sensors and measurement devices, ensuring high accuracy in data collection. The integration of sophisticated diagnostic tools like vibration analysis, as highlighted by Nawrocki et al. (2023), demonstrates the effectiveness of early detection methods for mechanical issues, thereby enhancing system reliability and maintenance planning. Moreover, Design of Experiments (DoE) stated a powerful methodology used in developing this research. The process involves conducting controlled experiments to collect data, which is then analyzed to identify optimal settings and interactions between variables. This approach ensures that the test rig is both efficient and reliable, providing valuable insights for improving cooling efficiency, energy use, and mechanical stability.

Besides, it has been proof that the compressor test rig is very suitable for educational purposes (Nagalakshmi & Yadav, 2014). But there is a lack of comprehensive studies that evaluate how different compressors interact with other HVAC components under varying environmental conditions. Additionally, there is a need for more research on different automotive compressors operates in different condition. Last, the test rig is aimed towards development and functionality. This is the main focus of this thesis. The following Chapter 3 was discusses the proposed development of Car Air-Conditioning Compressor Test Rig and experiment analysis using alternative test rig in detail.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This research is to develop Car Air-conditioning Electrical Compressor Test Rig (CAECT) and analyze vibration and others variable data on alternative test rig. This chapter explain how the whole procedure was done starting from identify requirements, design test rig layout, selecting components, assemble test rig and testing the test rig, this is process for first objective. For second objectives is starting from identify compressor type, design data acquisition, integrate sensors and instrument, collecting data, analyze and demonstrate data. The list of equipment used and flow for analysis part also presented in this chapter. The test rig has now been successfully developed, however, due to time constraints, only one compressor could be implemented. For the analysis, an alternative test rig with a similar working concept and operation will be utilized. Moreover, this research used quantitative method which the data output is shows for developed test rig and analysis on alternative test rig is be analyzed.

3.2 Research Structure

First objective (Red line) process begins with identifying requirements, where the specifications and performance criteria for the test rig are gathered which how it want to be structure and operate. This step involves understanding the operational conditions and ensuring all necessary parameters are considered. Next, the design test rig layout phase involves creating detailed schematic diagrams and layout plans that accommodate all components and sensors, ensuring an efficient and functional setup. Selecting components follows, where appropriate materials, mounting, and apparatus needed are chosen based on compatibility and performance needs. The assembly test rig phase involves constructing the test rig according to the design, integrating all selected components and systems to create a cohesive unit.

Finally, initial tests was conducted to ensure the test rig functions as intended, validating its performance against the defined criteria, and making any necessary adjustments to optimize its operation. A flowchart summarizing the overall process implemented throughout this work is shows in Figure 3.1

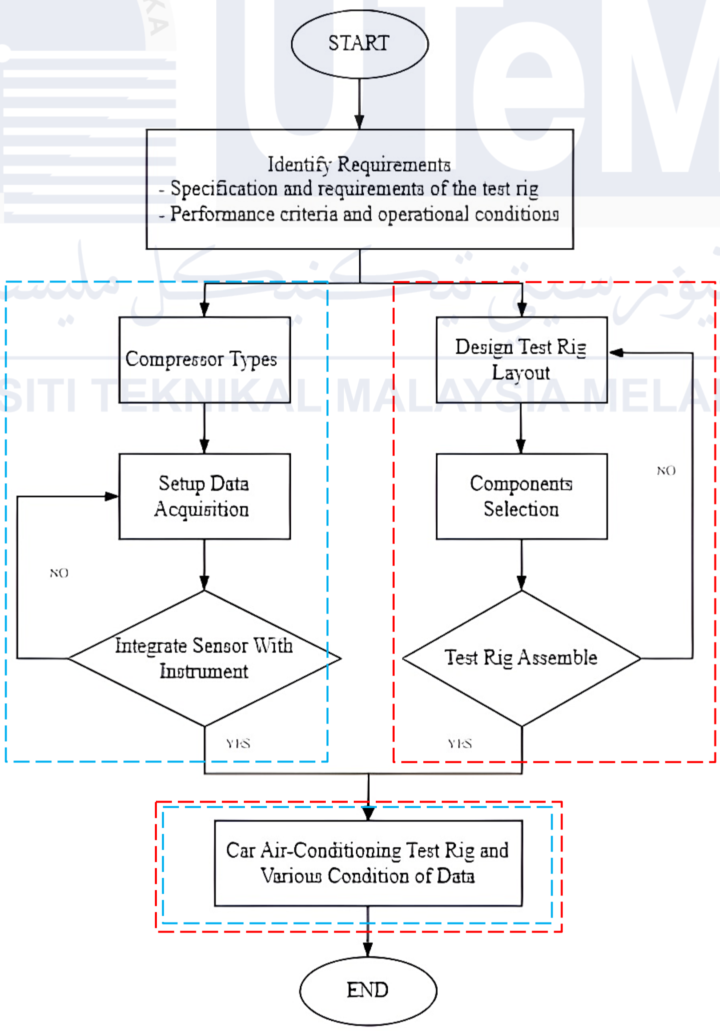


Figure 3.1 Overall process for developing the test rig

Second objective (Blue line) process begins with identifying different compressor types which is swash plate compressor. A data acquisition system is used to collect and process data from these compressor is used online vibration monitoring equipment. Tests are then conducted on the compressor to identified amount of refrigerant and RPM affecting vibration level and temperature. This data is then was analyzed to evaluate and compare factor and variable performance, with results demonstrated to showcase the effectiveness of the data acquisition system.

3.2.1 Schematic Structure

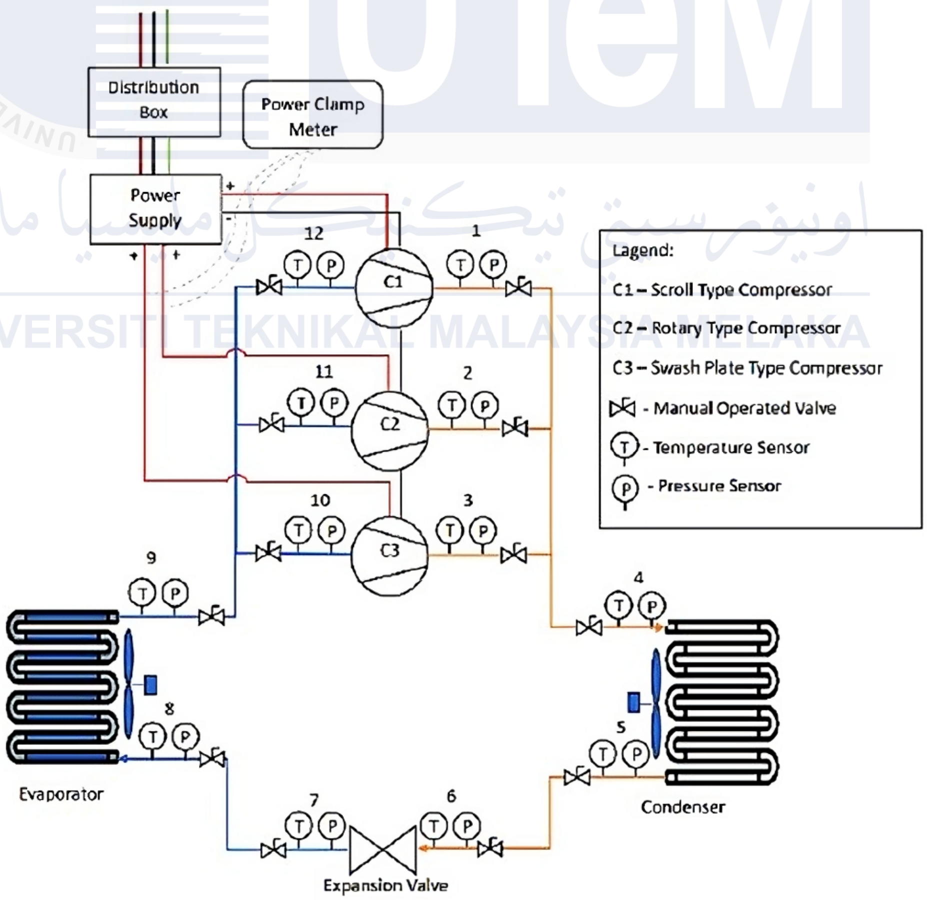


Figure 3.2 General schematic diagram of test rig equipment

Referring to the Figure 3.2 the schematic diagram illustrates the test rig setup for evaluating car air-conditioning compressors, including scroll, rotary, and swash plate types. The system begins with a power supply from the distribution box through a power clamp meter to measure consumption. Each compressor operates in parallel, with high-pressure refrigerant flowing through temperature and pressure sensors. Sensors placed throughout the system monitor temperature, pressure within the system ensuring accurate performance data collection for each compressor type. However, because of time constraints, the test developed only be done for one compressor which is Scroll compressor but the schematic diagram flow is same.

3.2.2 Parameter

Table 3.1 Parameter involved in CAECT

No.	Parameter	Units	Description
1.	Temperature	°C	Monitored at various points (Condenser, evaporator inlet/outlet).
2.	Pressure	Psi / Bar	Measured at different stages (Compressor suction/discharge).
3.	Power Consumption	W	Electrical power consumed by the compressor during operation.
4.	Amount of Refrigerant	Psi or g	Total weight or pressure level of the refrigerant used in system.
5.	Vibration	mm/s	Vibration levels of the compressor to detect mechanical issues.

Table 3.1 lists the key parameters that can be analyzed in CAECT for laboratory learning. Indication for vibration level is follows the standard given by International Organization for Standardization (ISO) 10816-1 severity charts by machine classes. Indication of amount of refrigerent used is follows the standard given by ISO 13043 road vehicles - refrigerant systems used in mobile air conditioning systems.

3.2.3 Design Structure

The design structure for the CAECT begins with a specific study to identify critical factors using the DoE approach, which directly informs how the design contributes to the experiment. Following this, a detailed sketch of the test rig was created in Figure 3.3 with unit in mm. This design ensures adequate space for housing the basic components air-conditioning system and sensors while allowing for easy access during testing and maintenance. The Gantt Chart also was been develop in Appendix 1 & 2 for standard timeline in completed this research.

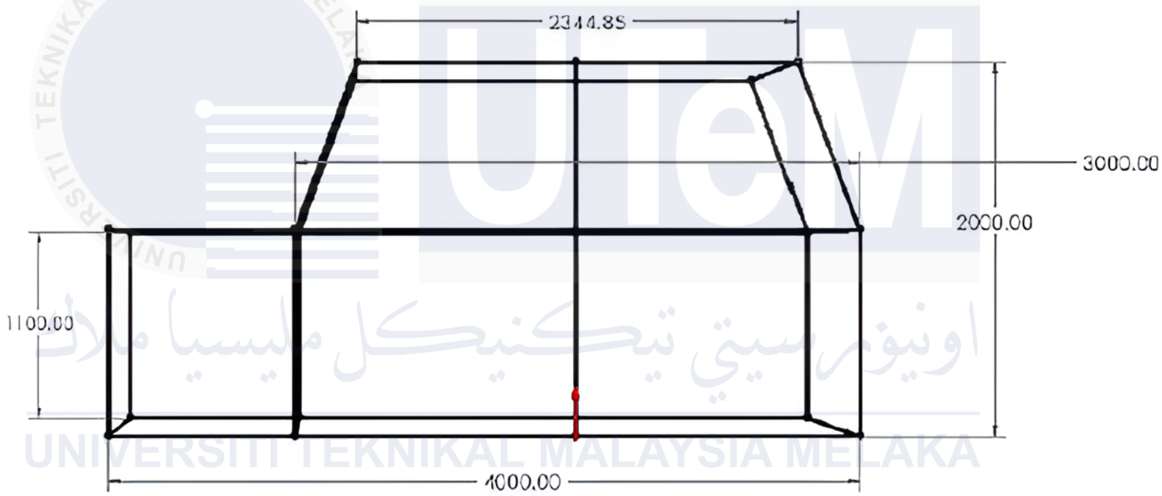


Figure 3.3 Dimensions and structure of the test rig

Referring to the Figure 3.4 is the 3D design structure for the car air-conditioning compressor test rig that constructed using 30 × 30 mm aluminum profiles, which provide a durable and lightweight framework. This design includes rollers at the base, allowing for easy movement and repositioning within the laboratory. The structure's dimensions are carefully estimated to ensure sufficient space for housing all necessary components, including compressors, sensors, and data acquisition systems. The 3D model is design using SolidWorks and all process assembly and analysis was conducted at UTeM, Melaka.

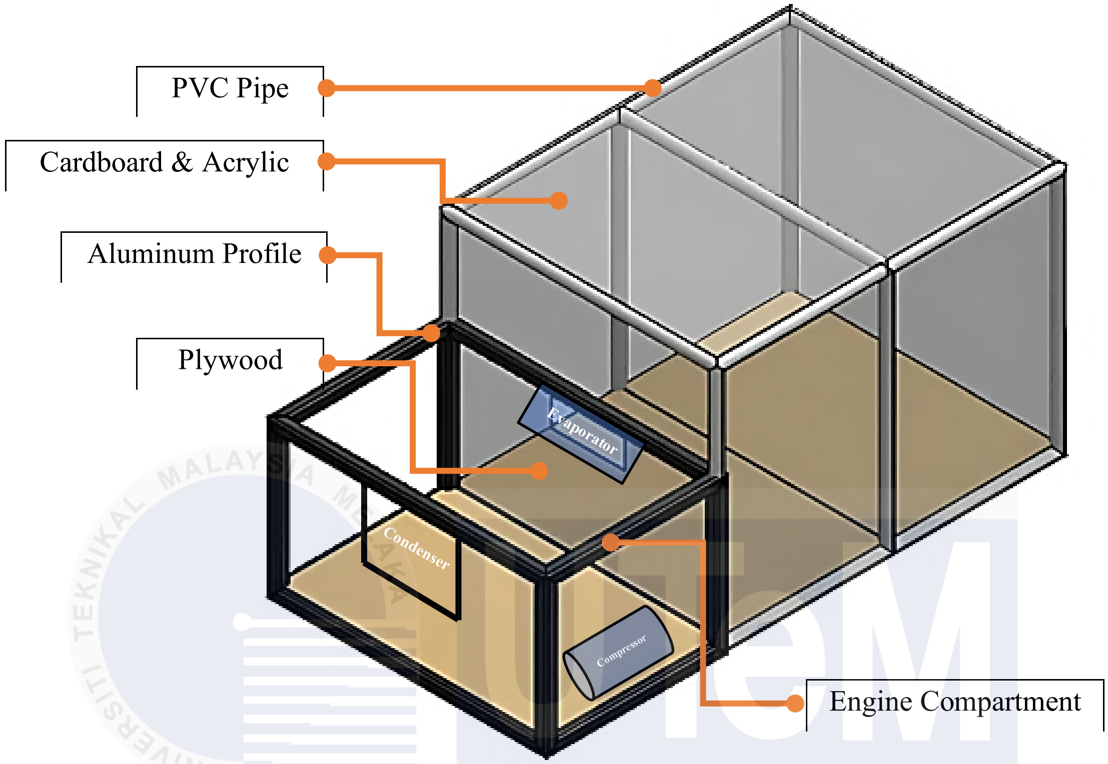


Figure 3.4 3D model of the test rig structure

Test rig structure was designed using a combination of materials to create a sturdy and functional enclosure. The base of the structure is made of plywood, providing a strong and stable foundation. The framework consists of aluminum profiles, which offer lightweight yet durable support to the overall design that only on engine compartment area. The walls are constructed from a combination of cardboard and acrylic, providing protection while maintaining transparency for visual observation of the interior. PVC pipes are used for cabin as connectors or additional support for the upper section, ensuring the framework remains secure and stable. On engine compartment area, it was the place to secured for compressor, condenser, evaporator and aircond piping.

3.2.4 Equipment

Table 3.2 List of major equipment for developing and analysis the test rig

No.	Equipment / Components	Basic Specifications
1.	12V Air Conditioning Compressor (Scroll Compressor)	– Type : DC 12V / 24 V – Cooling capacity: 5731 BTU / 8410 BTU – Speed range : 1000 - 3000 rpm – Current: 36 Amp - 46 Amp
2.	Cooling Coil Honda Jazz Hybrid 2016	– 38mm × 220mm × 223mm – Universal Blower
3.	Condenser Honda Jazz Hybrid 2016 with double fan	– 770mm × 332mm × 16mm – Number of blades (Per Fan): 7 blades
4.	Aluminium Profile, Plywood, Acrylic, Roller	– 30cm × 30cm – Structure purpose
5.	– Wireless Vibration Sensor – Gateway Router – Wireless WiFi	Type: ICP® (IEPE) Measurement Range: ±50 g to ±500 g Frequency Response: 0.5 Hz to 10 kHz Output Signal: Dynamic voltage proportional to acceleration or velocity
6.	Manifold Gauge, Low and High Pressure Head, R134A, R1234yf Gas	Dual gauge set for high and low-pressure readings that suit for R134A & R1234yf.
7.	DC to AC Converter	– Input: 12V/24V DC – Output: 120V/240V – AC Power capacity: 100-500W
8.	Flare Connection Pipe	Size 1/4" to 3/8"
9.	Vacuum Machine	Flow rate with 3CFM and 15 Microns
10.	Automatic Recovery Machine	Fully automatic mode with programmable settings for air-cond maintenance procedure.
11.	Thermocouple sensor	Measuring temperatures between -50°C to 500°C
12.	Testo Smart Pressure Sensor	Measuring compressor pressure on discharge and suction in Bar.

Referring to the Table 3.2 is lists of essential equipment used to develop and testing the Car Air-Conditioning Compressor Test Rig. The details specification of scroll compressor used can be refer on Appendix D.

3.2.5 Development Structure

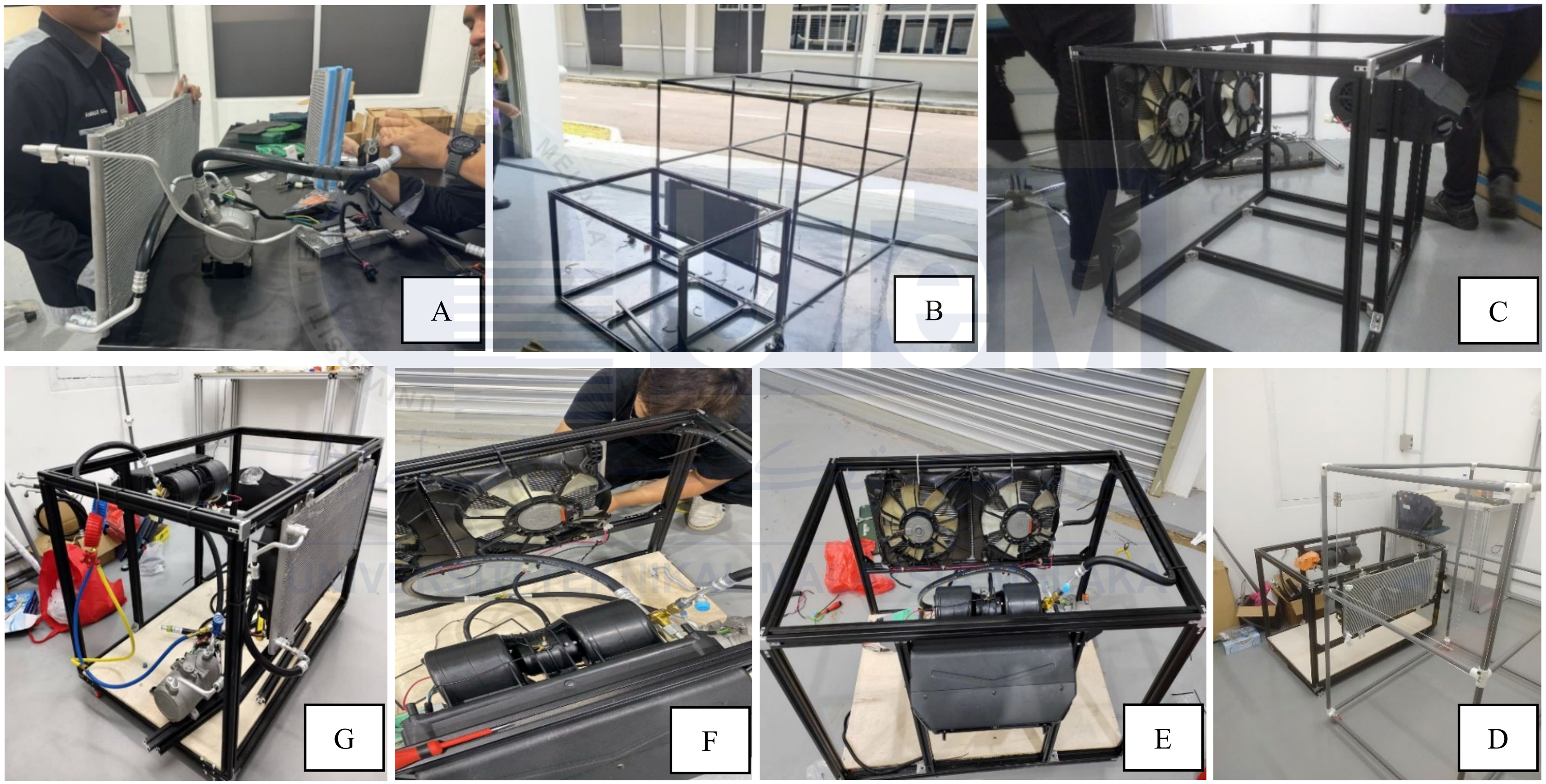


Figure 3.5 Test rig assemble process

The test rig development process was completed in several steps. First, referring to the Figure 3.5 the piping layout was study to determine the structure's dimensions (A). Then, the framework for the engine compartment and cabin was constructed using aluminum profiles (B). After that, the evaporator, compressor, and condenser were attached to the framework (C). Panels made of plywood and cabin made from acrylic were added to enclose the structure for protection and visibility (D). The refrigerant piping was assembled and securely connected (E), followed by wiring the electrical circuits for powering the fans and system (F,G).

3.2.5.1 Leak and Operation Testing

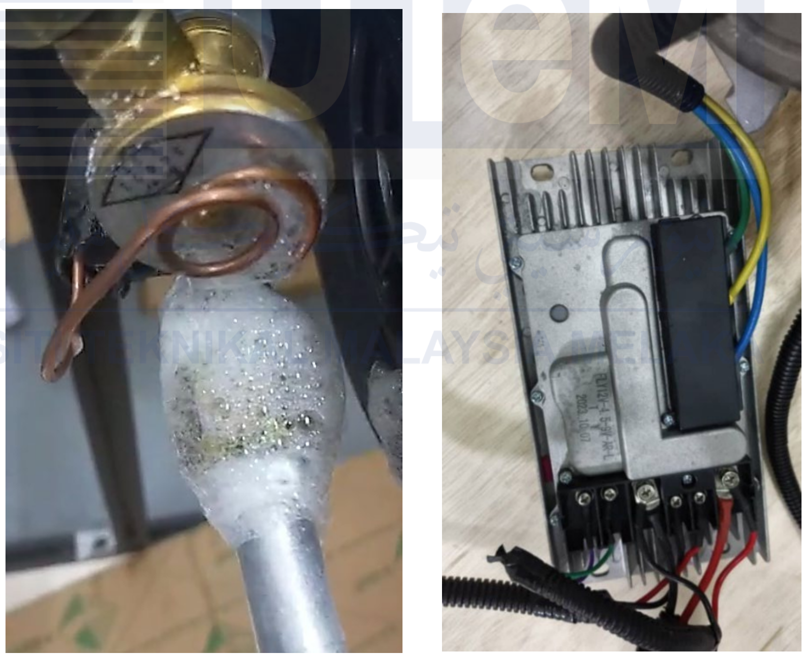


Figure 3.6 Leak testing (Left) and operation system test (Right)

The leak testing process involved using the bubble test method as in Figure 3.6 to identify potential leakage points in the piping system. The system was pressurized, and soapy water bubble was applied to the piping connections and joints. Any formation of bubbles indicated a leak, which was then addressed and rectified to ensure a sealed system. Once the leak testing was completed and the piping was confirmed to be leak-free, the test rig was prepared for the operation system test.

For the operation test, the system was powered on using a DC to AC converter to verify the electrical wiring and system functionality. This step ensured that all electrical connections were secure and the components, such as the compressor and fans, operated correctly. The successful completion of these tests validated the system's readiness for further testing and performance analysis.

3.2.6 Process of Operate and Data Collection on Developed Test rig

Referring to the Figure 3.7 is flow for test rig operation and flow for data collection, the process begins with the vacuuming stage, where a vacuum pump was used to remove air and moisture from the refrigeration system. This ensures the system is free of contaminants and ready for refrigerant charging (A). Next, the charging process involves using a refrigerant scale to accurately measure and recharge the refrigerant by weight, ensuring precise amounts are added for optimal system performance (B). Thermocouple sensors are then strategically placed at various points within the system to monitor temperature and pressure at each component's. These sensors provide critical data, which is further analyzed using equipment designed to capture accurate temperature and pressure readings (C,D). The collected data is display either using manual thermocouple sensor device or data logger shows that the real time data of the system, offering insights into the system's operation and facilitating precise performance evaluation (E).

Figure 3.8 and Table 3.3 illustrate the locations of the thermocouple sensors and Testo pressure sensors on the developed test rig. The temperature data was recorded using a data logger, while the pressure data was obtained through the Testo Smart app.

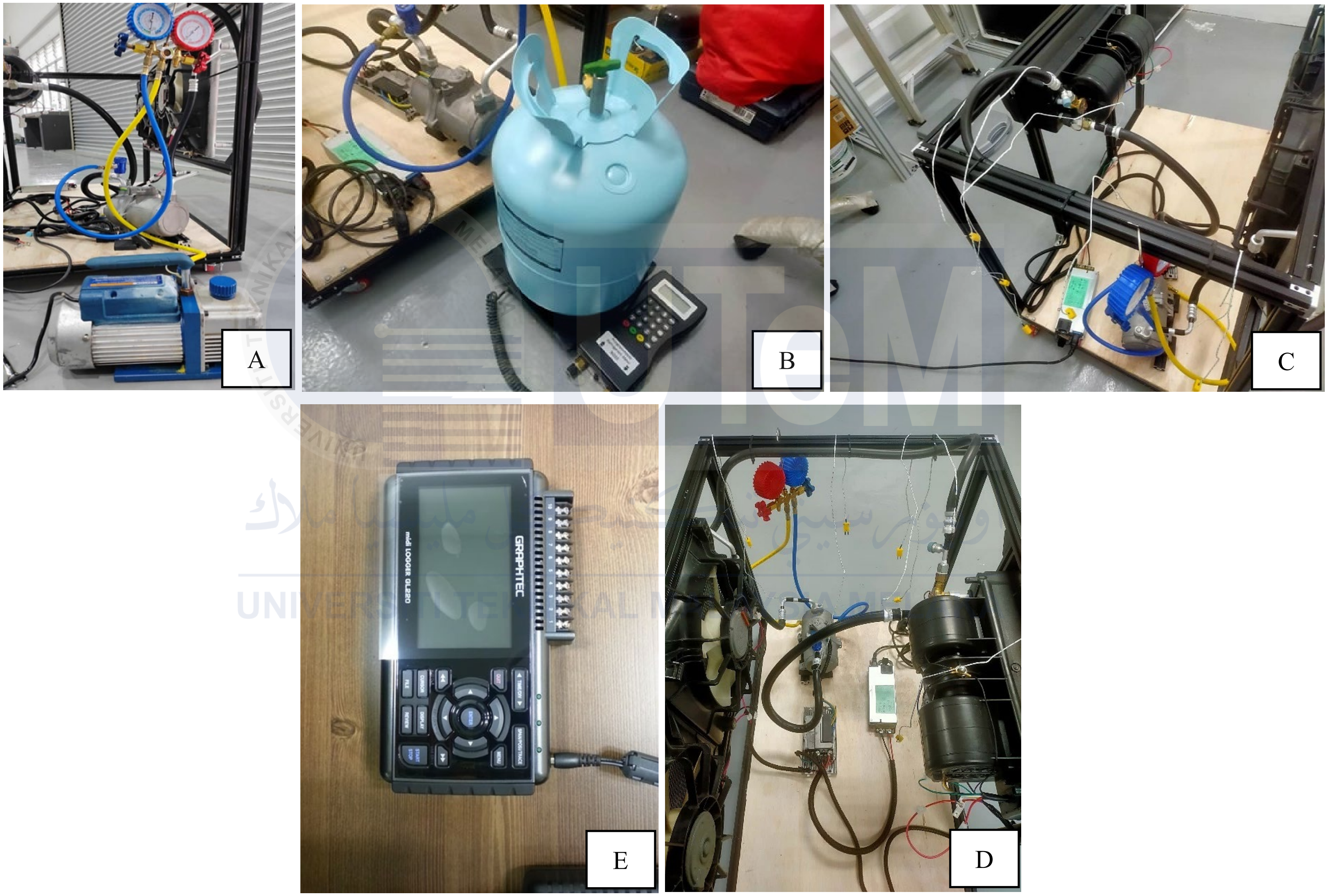


Figure 3.7 Flow of operation and data collection

3.2.6.1 Temperature and Pressure Sensor Placement

Figure 3.8 shows the points of thermocouples that have been installed. The system is installed with thermocouples and pressure sensor called Testo Smart at the various essential parts of the system. To measure the pressure and temperature, a data logger ability was used.

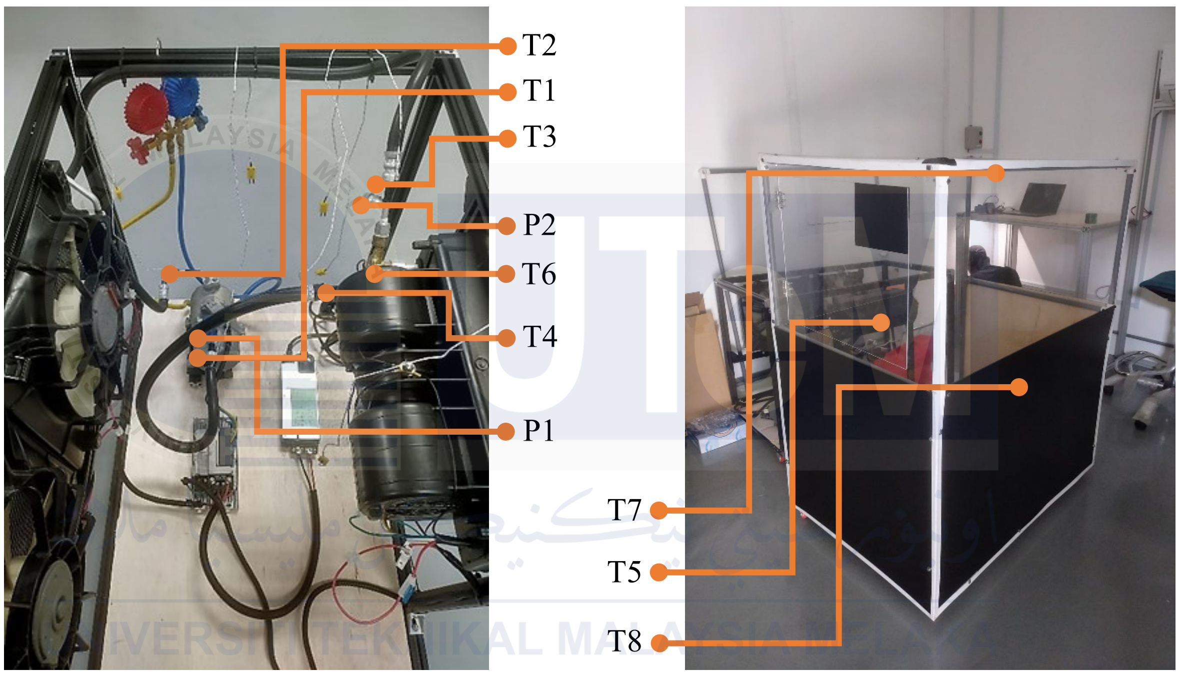


Figure 3.8 Sensor location on developed test rig

Table 3.3 Description of each sensor

No.	Sensor Description	No.	Sensor Description
T1	Temperature on compressor inlet (°C)	T6	Temperature of air after evaporator °C)
T2	Temperature on condenser inlet. (°C)	T7	Upper cabin air temperature (°C)
T3	Temperature on condenser outlet. (°C)	T8	Lower cabin air temperature. (°C)
T4	Temperature on evaporator outlet. (°C)	P1	Compressor suction pressure. (Bar)
T5	Temperature of evaporator inlet / Supplied air (°C)	P2	Compressor discharge pressure. (Bar)

3.2.6.2 Calculation of Coefficient of Performance (COP) of the system

For the validation that proof the system can be enhance for laboratory learning, the COP was calculated using the formula according to refrigerant principle on (1) and (2) respectively. The parameter in the formula were get from data output of the system and from R134A Pressure-Enthalpy (PH) diagram shows on Appendix 4. This test rig has been testing in a control room. The temperature and humidity of the room need to be monitored and controlled between 24°C to 26°C respectively. The system will be charged with R134a refrigerant and the initial refrigerant charge is weighed 220 gram into the system.

$$COP = \frac{Refrigerating\ effect}{Work\ done\ by\ compressor} \tag{1}$$

$$= \frac{Qin}{W} \ or \ = \frac{h1-h4}{h2-h1} \tag{2}$$

In a refrigeration cycle, h1 represents the enthalpy at the compressor inlet, where the refrigerant is a low-pressure, low-temperature vapor. After compression, the refrigerant exits as a high-pressure, high-temperature vapor, represented by h2. At the condenser outlet, the refrigerant becomes a high-pressure, low-temperature liquid, represented by h3. Finally, after passing through the expansion device, the refrigerant transforms into a low-pressure, low-temperature liquid-vapor mixture, represented by h4. These enthalpy values and data point are crucial for analyzing the system's performance and efficiency specifically COP.

3.2.7 Experimental Structure

The experimental flow of the test rig equipment referring to the Figure 3.8 is the flow to collect data from developed test rig only for laboratory session, a details experimental analysis that was conducted in this research are explain at 3.2.7.3 which is alternative test rig setup flow and procedure.

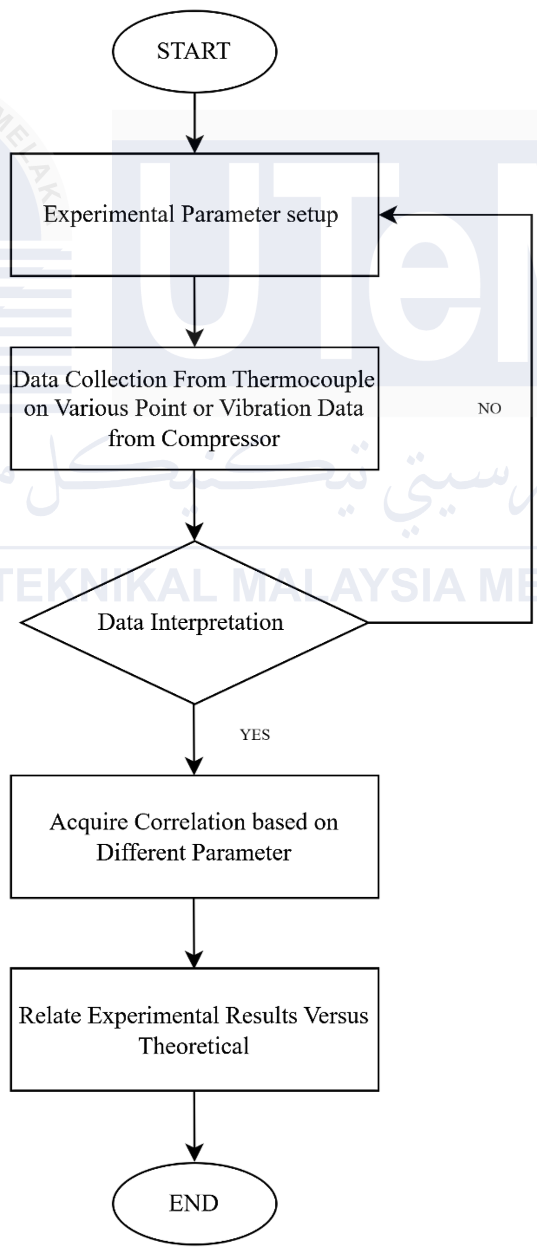


Figure 3.9 General laboratory experimental flowchart for developed test rig

3.2.7.1 Experimental Parameter on Alternative Test Rig

Referring to Table 3.4, the experimental parameters were considered using the DoE approach to systematically investigate the effects of various factors on the performance of the air conditioning system. The ambient temperature is constant on 25°C to get accurate data and with normal oil compressor level the changes only on refrigerant and RPM. Each of these factors is varied to determine its impact on the response variable, which in this case on Table 3.5 is the cooling temperature, compressor temperature and RMS level of the car air conditioning system. The levels on experiment factor represent the range of conditions under which the factors are evaluated. The specific values for the levels are determined based on practical and theoretical considerations for the experiment.

Table 3.4 Factors experimental designs for analysis in alternative test rig

Runs	Factors	Units	Levels
3	Amount of Refrigerent (R134a)	gram	Undercharged, Normal, Overcharged
	Revolution Per Minute	RPM	Idle, Medium, High, Very High
	Ambient Temperature	°C	Constant
	Oil Compressor	gram	Normal

Table 3.5 Variable data from experiment analysis

Variables	Units
Cooling Temperature Evaporator Produced	°C
Compressor Temperature	°C
Vibration Level in RMS	mm/s

3.2.7.2 Alternative Test Rig Features

In this study, an alternative test rig was utilized as shows in Figure 3.10 as part of the methodology to overcome time constraints and expedite the analysis process. The alternative test rig is machine that was developed for UTeM laboratory session, it shares the same operational concept as the primary electric compressor test rig which is CAECT but employs a conventional compressor instead. This approach ensured that the critical aspects of the analysis, such as system behavior, cooling performance, and vibration level, could still be accurately assessed and aligned with the objectives of the research.

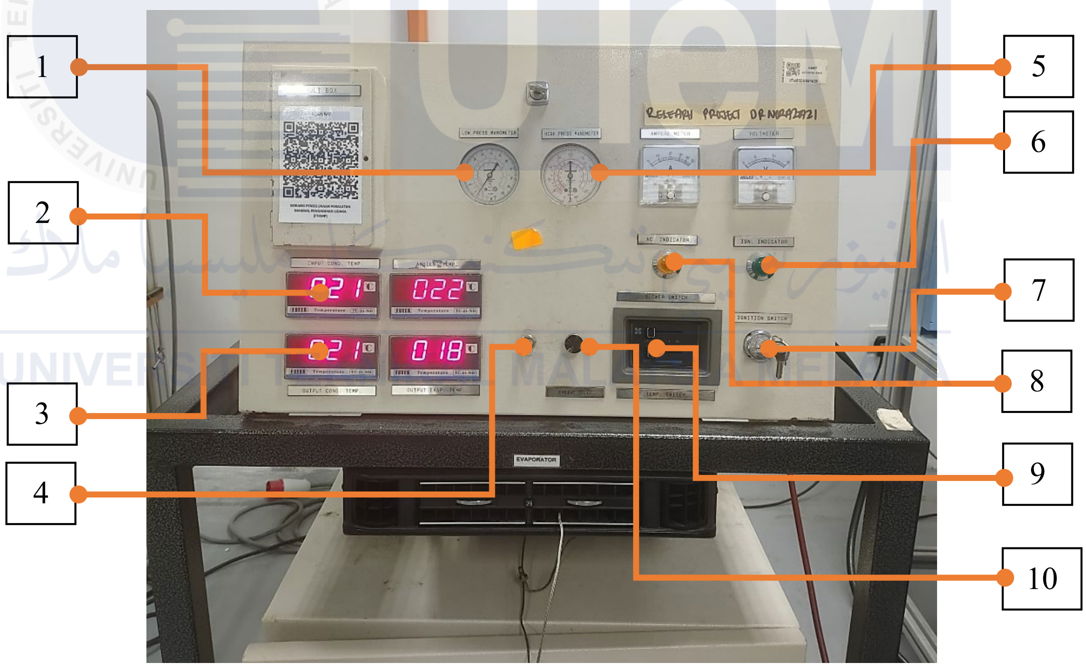


Figure 3.10 Alternative vehicle air conditioning test rig

Table 3.6 Display components

No.	Components	No.	Components
1	Low Pressure Manometer	6	Ignition Indicator
2	Input Condenser & Ambient Temperature	7	Ignition Switch
3	Output Condenser & Evaporator Temp	8	AC Indicator
4	Compressor Switch	9	AC Temperature Switch
5	High Pressure Manometer	10	Engine Speed (RPM)

The alternative test rig is equipped with fundamental components essential for the operation of a vapor compression refrigeration system. These include an evaporator, condenser, expansion valve, and cooling coil, all of which work in tandem to facilitate the refrigeration cycle. The compressor utilized in this setup is a swash plate compressor, known for its common compressor used in commercial vehicle because of efficiency, reliability, and smooth operation, ensuring consistent refrigerant circulation and performance throughout the system.

3.2.7.3 Alternative Test Rig Component and Setup

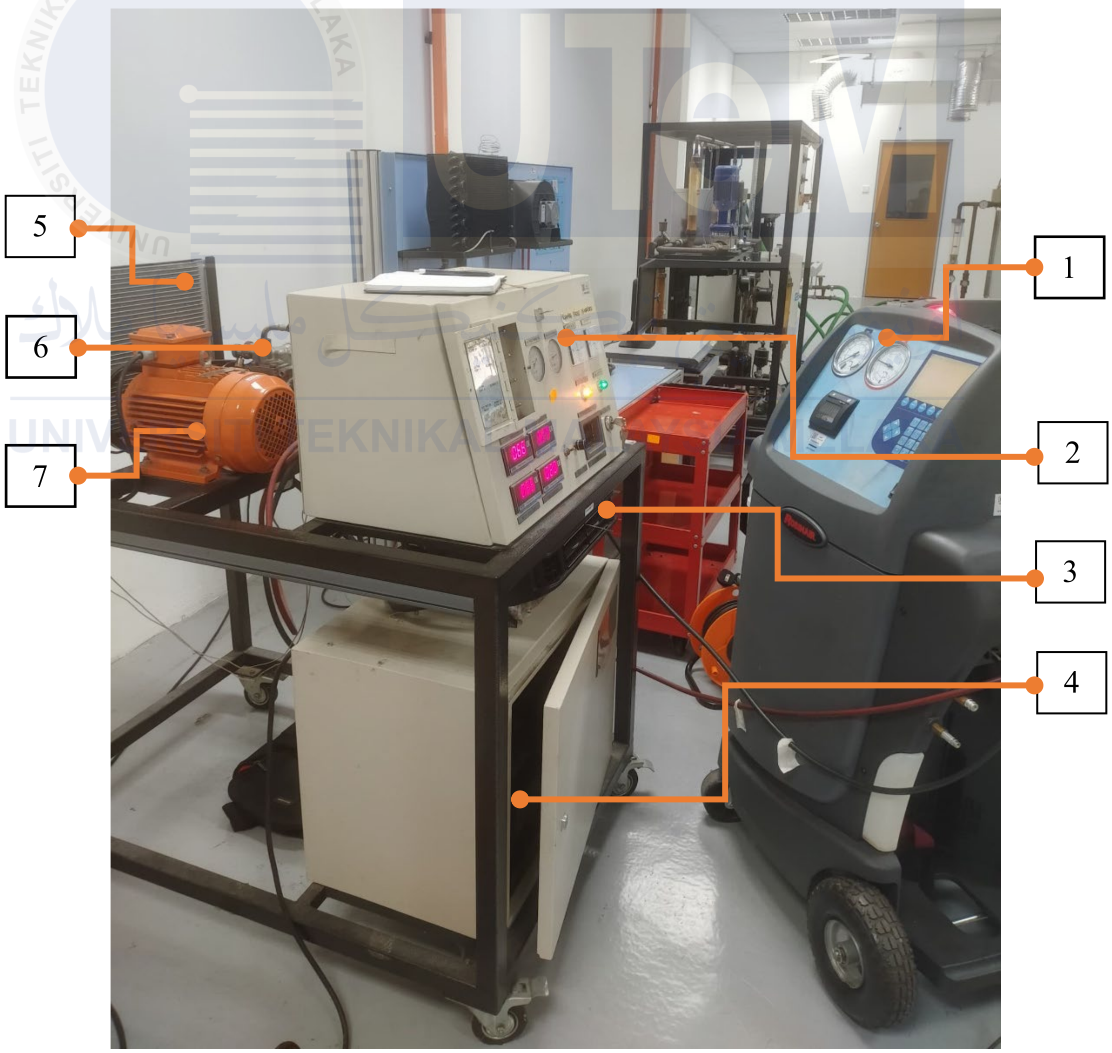


Figure 3.11 Alternative experiment test rig components

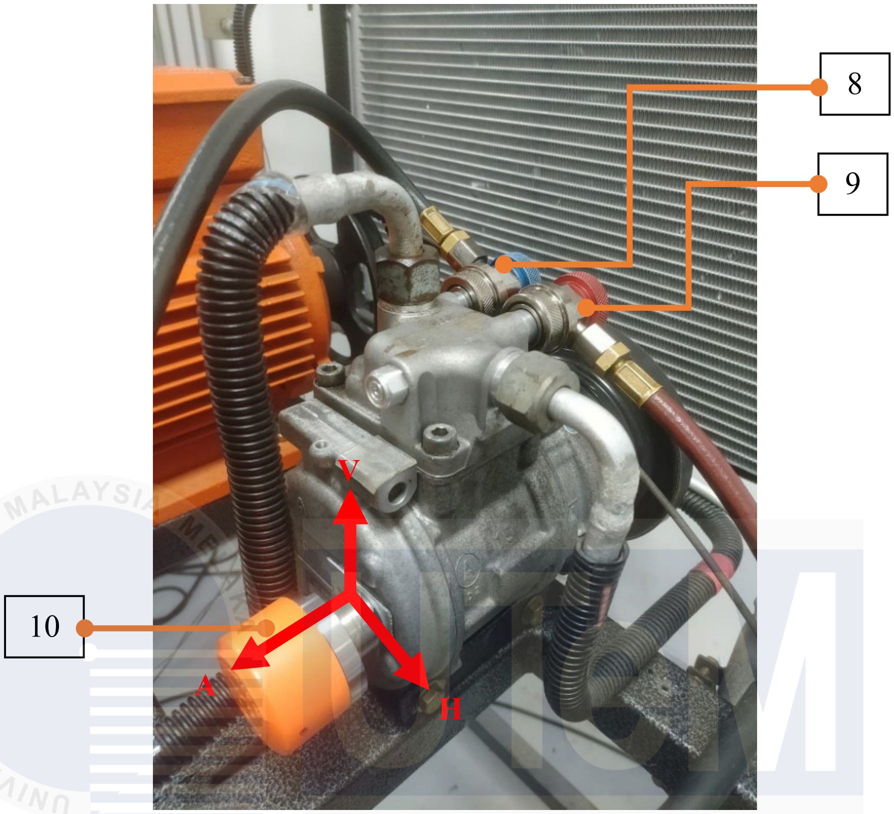


Figure 3.12 Compressor component and sensor placement

The alternative test rig is located at FTKM HVAC building in Industrial HVAC laboratory. The components attached as Figure 3.11 and 3.12 was same as CAECT. The only difference is type of the compressor used and the structure.

Table 3.7 Alternative test rig component function

No.	Components	Function
1	Automatic Recovery Machine	Recovers and recycles refrigerant.
2	Data Display	Provides real-time readings of system parameters.
3	Cooling Coil with Blower	Delivers cooled air.
4	DC Battery	Power supply for entire system.
5	Condenser with Fan	Dissipates heat from the refrigerant.
6	Swash Plate Compressor	Refrigerant circulation through system.
7	Belt System	Mechanical power to drive the rotary compressor.
8	Low Pressure Side	Section where refrigerant is in a low-pressure.
9	High Pressure side	Section where refrigerant is in a high-pressure.
10	Vibration Sensor (V1)	Monitors vibrations to detect mechanical issues.

3.2.7.4 Data Acquisition Setup for Vibration Online Monitoring

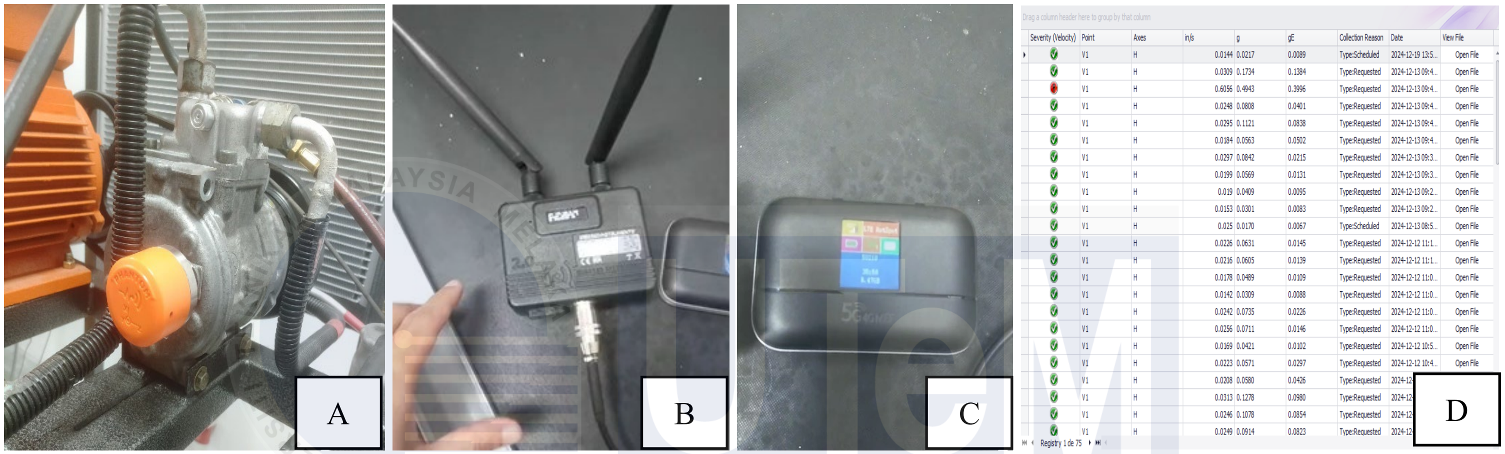


Figure 3.13 DAQ setup process

The DAQ setup for real-time vibration monitoring as in Figure 3.13 begins with the placement of a V1 vibration sensor on the compressor, ensuring accurate detection and measurement of vibration data (A). Once the sensor is in position, a gateway router was configured to serve as the central communication hub, enabling the seamless transfer of data (B). A wireless router is then were activated to provide a stable and secure connection, ensuring reliable data transmission for continuous real-time monitoring (C). With the hardware in place, the vibration sensor transmits live data, enabling operators to effectively monitor the compressor's performance metrics. The DigiVibeMX 11 application is utilized to collect and analyze this data, displaying the vibration patterns of the system, including the total Root Mean Square (RMS). The RMS values for each condition are compared to evaluate performance and the sample of the vibration results from the software is shows on Appendix F in 320g refrigerant at 1000 RPM.

3.2.7.5 Experimental Analysis Flow

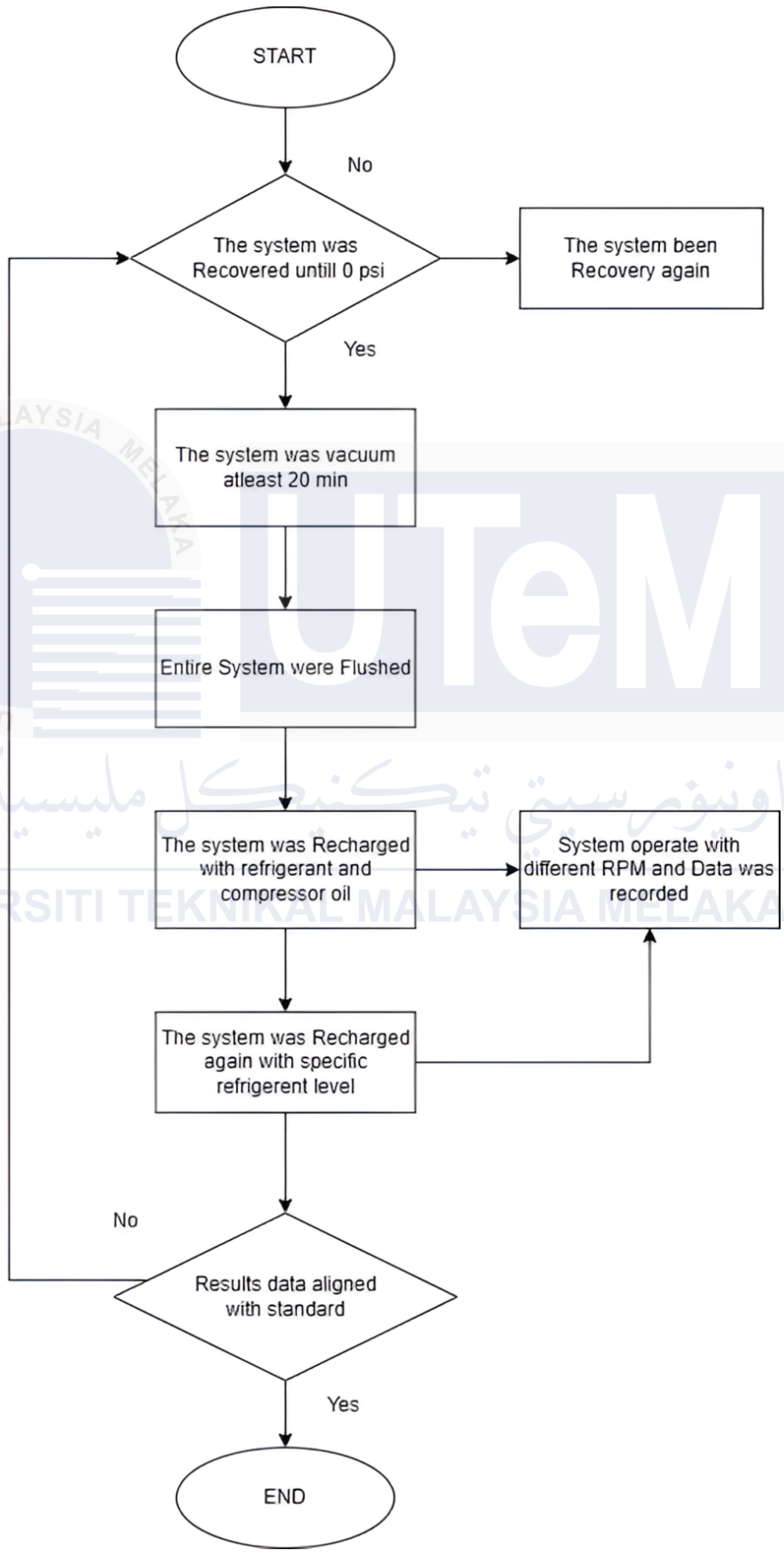


Figure 3.14 Detailed experimental analysis flow

The flow in Figure 3.14 and 3.15 is the procedure of experiment analysis for this research using the alternative test rig, it involved Recover, Vacuum, Flushing and Recharge process using automatic recovery machine. First the system is recovered until the low pressure indicator pressure reaches 0 psi. If the recovery is not successful, the system undergoes recovery again. Once the recovery is completed, the system is vacuumed for at least 20 minutes to remove any moisture or contaminants. Following this, the entire system is flushed to ensure cleanliness and operational integrity. The system is then recharged with refrigerant and compressor oil are injected to restore functionality. Subsequently, the system is recharged again with a specific refrigerant level for analysis purpose. During operation, the system is tested at different RPM levels, and data is recorded for analysis. If the results align with the required standards, the process is completed. If not, adjustments are made ensuring a thorough and rigorous evaluation of the system's performance.

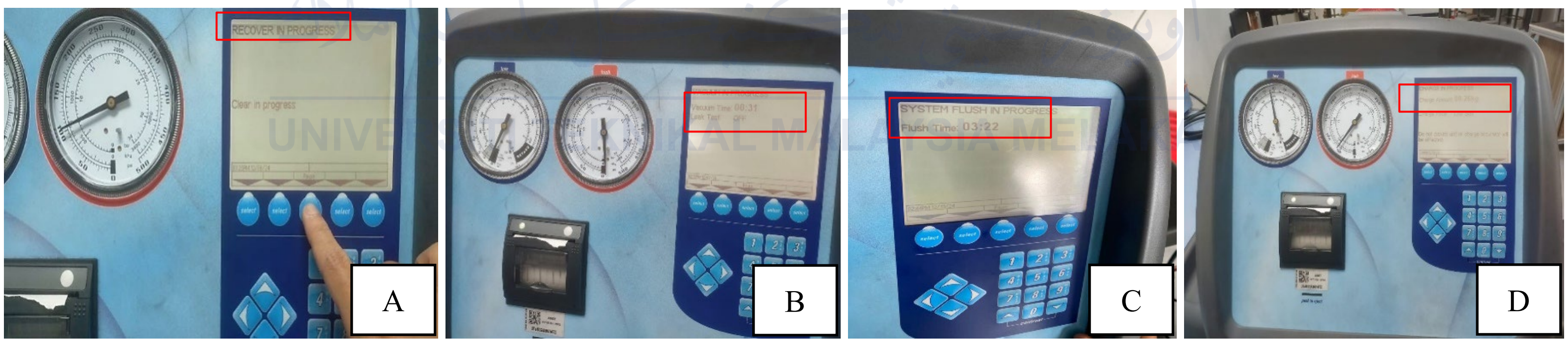


Figure 3.15 Recovery, Vacuum, Flushing and Recharge system process flow

3.3 Summary

The research methodology focuses on developing and analyzing a Car Air Conditioning Electrical Compressor Test Rig (CAECT) to achieve two primary objectives. The first objective involved the development of the test rig using DoE approach, starting with identifying requirements and operational parameters. This phase included defining specifications, designing the test rig layout, selecting components, assembling, testing and validate the test rig. The dimensions, modelling, equipment used and flow process for developing and taken the output data was shows as evidence that student incorporated to this research purpose.

For the second objective, time constraints prevented the full integration and testing of the primary test rig. To overcome this limitation, an alternative test rig with similar operational principles was utilized. Located in the UTeM HVAC laboratory, this rig allowed the collection of critical data, such as refrigerant levels, different RPM, compressor temperature, vibration levels, and cooling temperature. The alternative setup incorporated components such as a swash plate compressor, condenser, evaporator, and data acquisition systems to enable real-time monitoring using online vibration analysis equipment.

The experimental procedure involved key processes like recovery, vacuuming, flushing, and recharging to prepare the system for testing. Testing was conducted at various RPM levels and refrigerant conditions to evaluate system performance against theoretical expectations. The use of the alternative test rig used to achieve the second objective despite the limited time available for the primary test rig, maintaining the integrity and relevance of the research findings.

CHAPTER 4

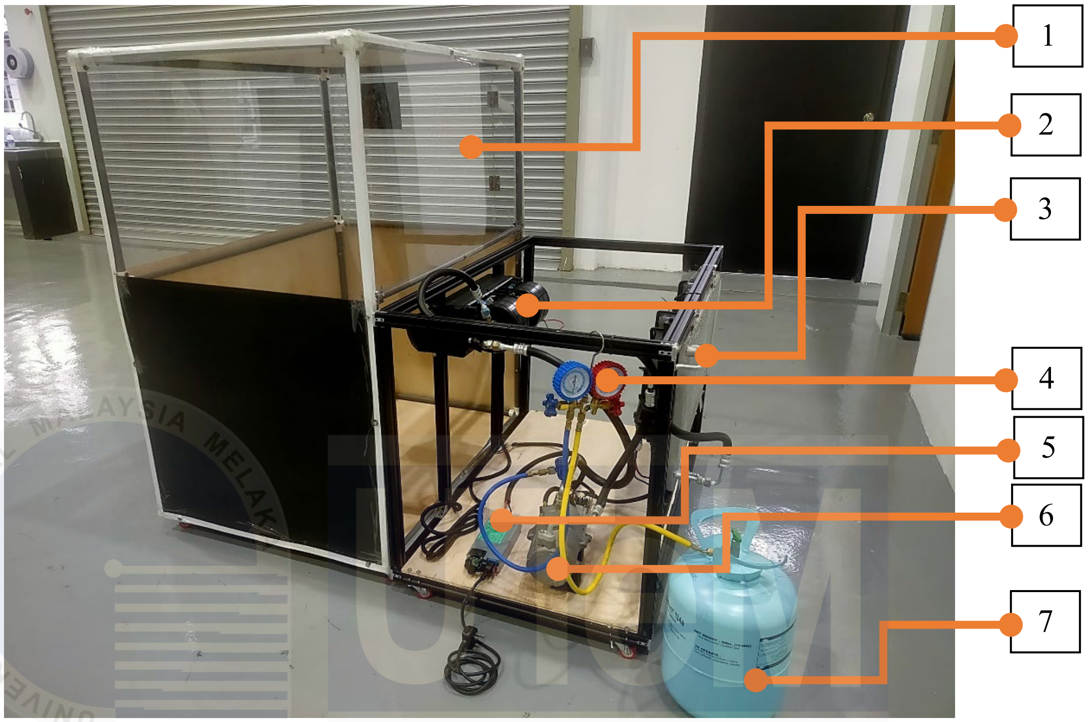
RESULTS & DISCUSSION

4.1 Introduction

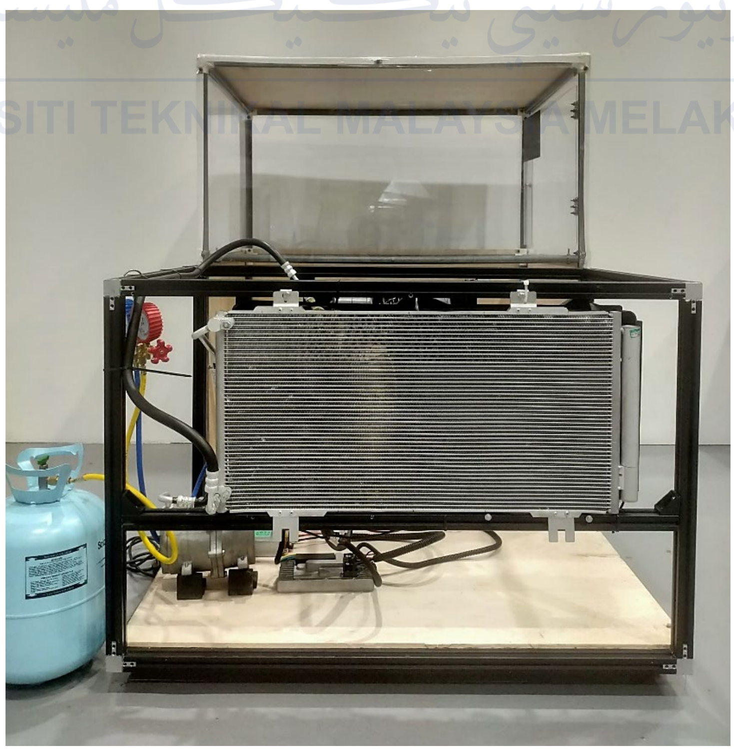
The results and discussion section presents the findings from the development of the Car Air Conditioning Electrical Compressor Test Rig (CAECT) and the subsequent vibration analysis conducted using an alternative test rig. This section is divided into two main parts, the first highlights the design and component integration of the CAECT with sensor placement data, showcasing its capability for use in laboratory learning. The second part focuses on the vibration analysis performed on the alternative test rig, which was employed due to time constraints and incomplete RPM control on the primary test rig.

The results of the vibration analysis are critically examined, emphasizing the impact of operational variables such vibration level and temperature characteristics. This analysis provides valuable insights into system behavior and performance under varying conditions. Furthermore, comparisons are drawn between expected and observed outcomes, with a particular focus on the finding that overcharge and undercharge refrigerant levels do not significantly affect compressor vibration, challenging conventional expectations. The discussion concludes with implications vibration analysis results to the automotive industry.

4.2 Overview of the Car Air Conditioning Electrical Compressor Test Rig (CAECT)



(a) Full view of CAECT



(b) Front view CAECT

Figure 4.1 CAECT Components

The test rig displayed in the Figure 4.1 and description as in Table 4.1 is a real product of CAECT, designed for analyzing the performance of automotive air conditioning systems using electrical compressor (Scroll compressor). The rig features is lightweight aluminum profile framework, providing stability and portability within the laboratory. The central component is the compressor unit, which is connected to high and low pressure lines, enabling accurate testing of refrigerant flow and system performance. A manifold gauge were set is prominently positioned at the top, allowing for precise monitoring and control of pressure levels.

A refrigerant tank containing R134a is situated at the forefront, supplying refrigerant for system operation and analysis. The rig is equipped with flexible piping, secure flare connections, and integrated heat exchange components such as a condenser and evaporator, simulating real-world conditions of automotive air conditioning systems. Additionally, the rolling base of the structure facilitates ease of movement and repositioning within the learning process. This test rig is designed to evaluate critical parameters, including pressure, temperature, power consumption, and vibration, providing a comprehensive platform for laboratory learning.

Table 4.1 CAECT components description

No.	Components	Function
1	Cabin Car	Cool air supplied area.
2	Evaporator & Blower	Delivers cool air.
3	Condenser with Fan	Dissipates heat from the refrigerant.
4	Manifold Gauge	High and low pressure connection for pre-process.
5	DC Converter	Power supply for the system.
6	Electric Scroll Compressor	Refrigerant circulation through system.
7	R134a Gas	Refrigerent for the system.

4.2.1 Output Data from CAECT

Table and Figure 4.2 lists a temperature and pressure sensor data points in CAECT system. The measured value of the system is taken when compressor on normal level of oil (150ml) and normal refrigerant level (220g) with 25°C constant ambient temperature. The cool air temperature supplied on T5 aligned with maximum cooling temperature on alternative test rig and R134a performance standard which is 8°C on Table 4.4 and Figure 4.12 this shows the test rig system is functioning effectively and achieving the desired cooling performance.

Table 4.2 Output data point

No.	Measured Value	No.	Measured Value
T1	6.7 °C	T6	26.4 °C
T2	31.0 °C	T7	15.8 °C
T3	27.4 °C	T8	17.1 °C
T4	9.0 °C	P1	2.11 Bar
T5	8.1 °C	P2	5.85 Bar

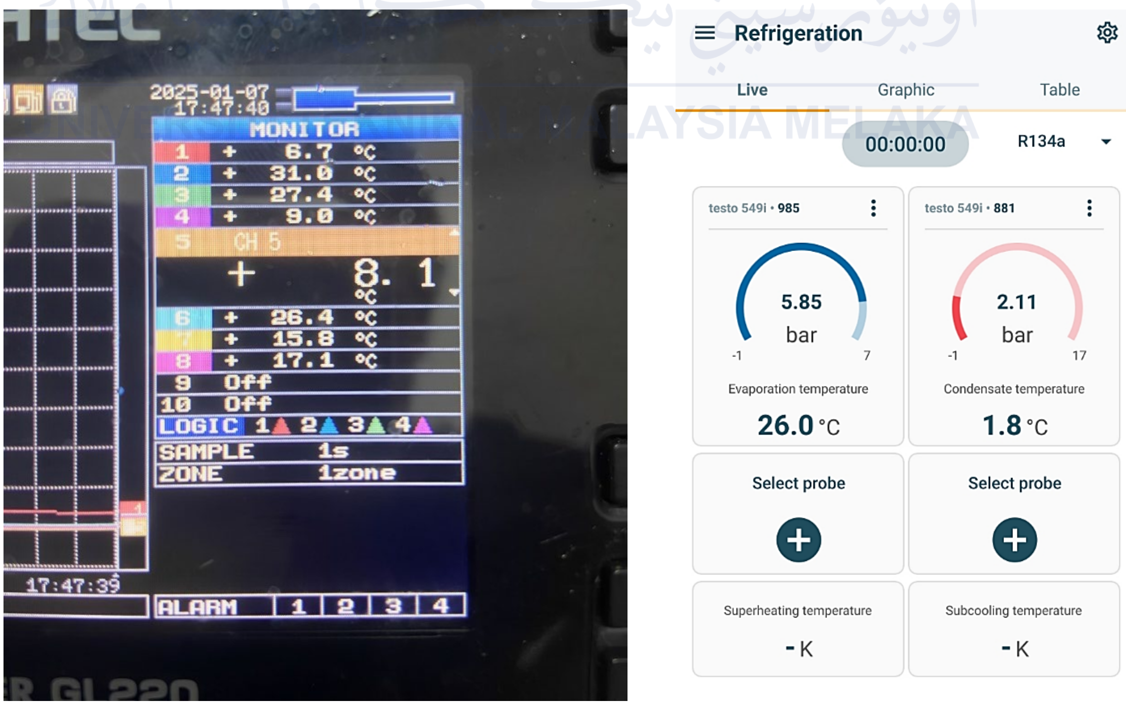


Figure 4.2 Display value for each data point in temperature result on data logger and pressure results on Testo Smart app

4.2.1 Coefficient of Performance (COP) in CAECT System

The sample calculation stated on Appendix E shows the COP is 5, its mean the system deliver 5 units of cooling for every 1 unit of electrical energy consumed. This is significantly higher than the typical COP range of 2 to 4 for conventional vehicle air conditioning systems. The high COP can be attributed to several factors. Firstly, the use of a hybrid compressor system likely optimized the refrigerant cycle, reducing energy losses and enhancing the cooling performance. Hybrid effective at modulating their load based on cooling demand, leading to greater efficiency compared to traditional fixed-speed compressors. Secondly, the test rig operate in stable ambient temperatures which minimized thermal losses and improved overall energy utilization making it to get higher COP.

The achievement of a COP of 5 in CAECT, offers significant educational value. It provides a benchmark for students to analyze and compare the efficiency of different air conditioning refrigerant, allowing student to explore the factors that contribute to performance improvements. In a controlled lab environment, students can calculate and measure COP values, gaining hands-on experience with thermodynamic principles and energy efficiency analysis.

Moreover, the COP of CAECT aligns with the findings of (Meng et al., 2023) where the authors also recorded a COP of 5.24 for R134a. This consistency validates the system's design and accuracy, demonstrating its capability to save energy while maintaining excellent functionality.

4.3 Validation of Test Rig System

It is essential to ensure that the test rig operates as intended and meets the necessary standards for reliability and accuracy. The validation process includes various checks and tests to confirm the functionality of all integrated components and the overall system. One critical aspect of this validation is leak testing that was conducted, which ensures that the system is properly sealed and capable of maintaining the desired pressure and refrigerant levels without any losses.

Figure 4.3 System pressure test indicator (Day 1)

On day 1 as in Figure 4.3 the system was pressurized to around 50 psi using a controlled supply of compressed air. This initial pressure setting serves as a baseline for evaluating the sealing performance of the test rig and ensuring that all connections, joints, and components are securely fitted and leak-proof.

Figure 4.4 System pressure test indicator (Day 2)

After 24 hours of monitoring the system following the leak test, the pressure showed a slight reduction from 50 psi to 47 psi, indicating a minimal drop. However, this slight decrease was within acceptable limits and did not point to any active leaks in the system. The pressure remained stable, confirming that the piping and connections were effectively sealed. This result validated the integrity of the system, ensuring it was leak free and ready for operation.

4.4 Integration of the CAECT Into Laboratory Learning

The CAECT replicates the functionality of a vehicle's air conditioning system, enabling students to gain hands-on experience with real world applications. By integrating this system into laboratory sessions, students can develop a deeper understanding of automotive air conditioning, including maintenance protocols, diagnostic techniques, and performance optimization. This approach bridges the gap between theoretical learning and practical skills, preparing students for the challenges of the automotive and HVAC industries.

Table 4.3 CAECT feature for laboratory learning

Feature	Description
Manual Operation for Maintenance	Facilitates flushing, refrigerant recovery, recharging, and vacuuming, offering practical training in essential AC maintenance tasks.
Support for Automatic Recovery Learning	Allows the use of automated tools for refrigerant recovery and recycling, introducing students to industry standard technologies in HVAC automotive.
Diagnostics and Troubleshooting	Encourages the identification and resolution of common faults in AC systems, developing critical problem-solving skills.
Refrigerant Handling Training	Provides practical experience in managing refrigerants responsibly and safely, aligned with environmental and industry regulations.
Pressure, Temperature and Performance Analysis	Enables observation of pressure changes and performance variations, enhancing the understanding of system efficiency under varying operational conditions.
Customizable Experimental Design	Supports tailored experiments on topics like energy efficiency and system optimization, offering flexibility to meet diverse educational objectives.
Maintenance Protocol Training	Allows practice in routine AC maintenance, such as oil checks and filter replacements, ensuring a comprehensive understanding of system care.

The test rig was originally intended to include sensors on each piping segment of the system to enhance monitoring and provide ease of application during laboratory sessions. While the sensors have been successfully implemented, the system could not achieve features to change different RPM level adjustments due to time constraints, and the system is currently operational within a limited RPM range.

4.5 Experimental Data Results

The experiment evaluated the performance of the system under three different refrigerant conditions, undercharged, normal, and overcharged. The analysis involved measuring the root mean square (RMS) of compressor vibration using online vibration software. These parameters were observed across various compressor speeds (RPMs) to assess their impact under each condition. The data provided insights into how the system responded in terms of vibration, cooling efficiency, and compressor thermal behavior across different operating and refrigerant levels.

Table 4.4 presents the experimental results for vibration data along the horizontal axis, while Table 4.5 provides the vibration data for the vertical axis. For each parameter, three readings were recorded over a 10-minute operation to ensure accuracy, and the average was calculated to provide a comparable value. Vibration measurements concentrated on these two axis, as they have the most significant impact on swash plate operation. It recorded refrigerant level on undercharged (280g), normal (320g), and overcharged (360g) conditions at rotational speeds of 1000 RPM, 1300 RPM, 1600 RPM and 1900 RPM. Generally, the results shows RMS vibration increased with speed across all conditions, while cooling temperature and compressor temperature were influenced by refrigerant levels and also RPM.

4.5.1 Horizontal Axis with Variable Data

Table 4.4 Experiment results with horizontal axis vibration data

Condition R134a	Rate Per Minutes (RPM)	Root Mean Square (RMS) of Compressor Vibration (mm/s) in Horizontal Axis				Cooling Temperature (°C) on Evaporator Outlet				Compressor Temperature (°C)			
		n = 1	n = 2	n = 3	$\bar{X}$	n = 1	n = 2	n = 3	$\bar{X}$	n = 1	n = 2	n = 3	$\bar{X}$
Under charged (280g)	1000	2.6	2.5	2.6	2.57	11	11	12	11.3	42	41	43	42
	1300	3.71	3.63	3.69	3.68	11	12	12	11.7	44	46	43	44.3
	1600	6.79	6.74	6.8	6.78	11	11	12	11.3	46	45	45	45.3
	1900	7.5	7.45	7.76	7.57	11	12	11	11.3	47	46	47	46.7
Normal (320g)	1000	2.7	2.7	2.75	2.72	9	8	8	8.3	39	39	39	39
	1300	3.75	3.74	3.7	3.73	8	8	8	8	40	39	40	39.67
	1600	7.39	7.36	7.38	7.38	8	8	8	8	41	42	42	41.7
	1900	7.76	7.78	7.7	7.75	8	8	8	8	43	43	42	42.7
Overcharged (360g)	1000	2.62	2.6	2.65	2.63	10	11	11	10.7	43	44	43	43.3
	1300	3.82	3.8	3.82	3.82	11	10	11	10.7	44	44	44	44
	1600	6.68	6.65	6.67	6.67	10	10	11	10.3	45	46	46	45.7
	1900	7.66	7.64	7.65	7.65	11	10	9	10	46	47	47	46.7

For the normal refrigerant level, vibration values on the horizontal axis consistently increase as RPM increases, similar to overcharged and undercharged refrigerant levels in constant 25°C ambient temperature. The cooling and compressor temperatures show a positive impact, achieving maximum cooling efficiency and maintaining a minimum compressor operating temperature on 320g.

4.5.2 Vertical Axis

Table 4.5 Vibration data for vertical axis

Condition	Rate Per Minutes (RPM)	Root Mean Square (RMS) of Compressor Vibration (mm/s) in Vertical Axis			
		n = 1	n = 2	n = 3	$\bar{X}$
Undercharged (280g)	1000	1.99	1.87	1.94	1.93
	1300	4.53	4.55	4.50	4.53
	1600	36.12	36.13	36.20	36.15
	1900	28.68	28.65	28.66	28.66
Normal (320g)	1000	2.24	2.25	2.22	2.24
	1300	4.71	4.70	4.72	4.71
	1600	45.07	45.0	45.20	45.09
	1900	22.71	22.18	22.0	22.30
Overcharged (360g)	1000	1.58	1.58	1.59	1.58
	1300	4.66	4.67	4.70	4.68
	1600	34.70	34.72	34.71	34.71
	1900	22.92	22.91	22.93	22.92

At 1600 RPM, the RMS values for vertical axis vibration were 36.15 mm/s for undercharged, 45.00 mm/s for normal, and 34.71 mm/s for overcharged conditions. At 1900 RPM, the RMS values stated to 28.66 mm/s for undercharged, 22.30 mm/s for normal, and 22.92 mm/s for overcharged conditions that their rise and decrease inconsistently in different RPM. The data shows very high vibration values, which may indicate potential issues within the system. However, the research focuses solely on the relationship between refrigerant levels and vibration only. Similar to the horizontal axis, RPM has a greater influence on vibration compared to refrigerant levels.

4.6 Relationship of RMS Vibration Under Different Refrigerant Conditions with RPM

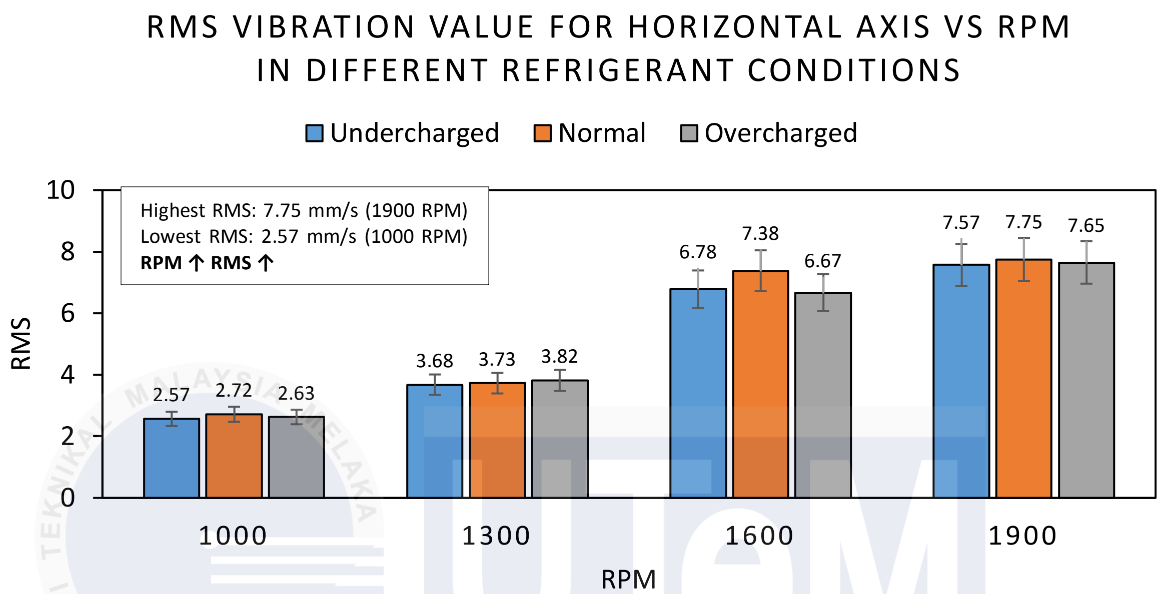


Figure 4.5 RMS vibration value for horizontal axis versus RPM for different refrigerant condition

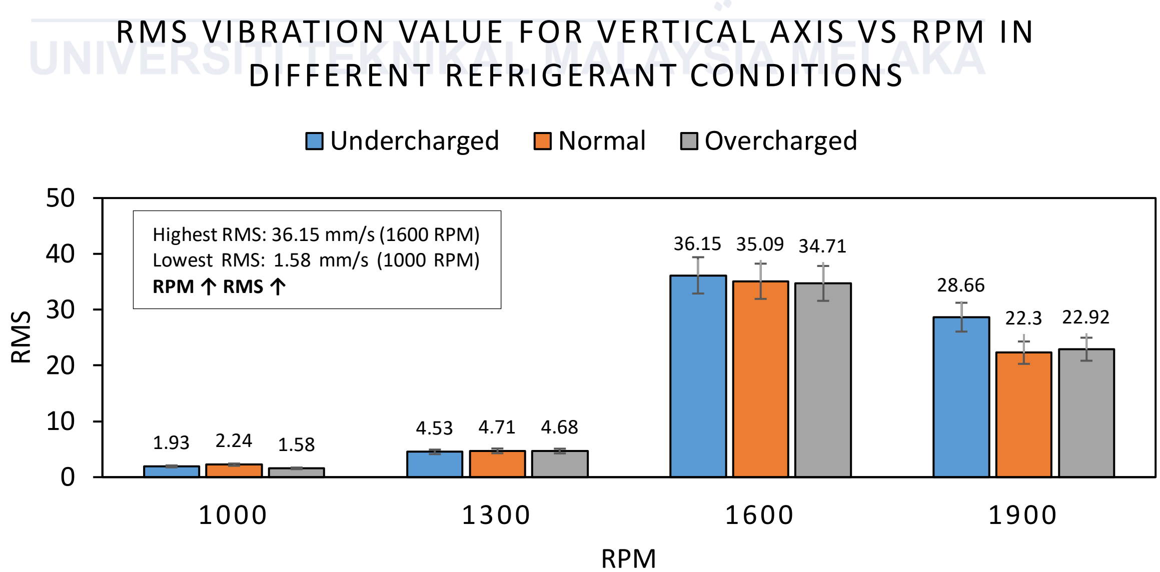


Figure 4.6 RMS vibration levels for vertical axis versus RPM for different refrigerant conditions

Referring to Figures 4.4 and 4.5, the graphs indicate that RMS vibration values in both the horizontal and vertical axis increase with RPM across all refrigerant conditions. Horizontal axis at 1000 RPM, the RMS value remains steady around 2 mm/s, also at 1900 RPM, it consistently reaches around 7 mm/s. This trend indicates that RPM has a biggest influence on vibration intensity, as higher rotational speeds generate greater dynamic forces. Overall, the trend highlights the significant impact of RPM on vibration align with the finding from Burdzik (2013) with refrigerant levels having a minor secondary effect.

The sudden increase in vertical axis and higher vibration value at 1600 RPM in vertical axis is due to the operation of the swash plate compressor. The swash plate creates axial forces as it drives the pistons to compress refrigerant, and at 1600 RPM, the operating frequency likely aligns with the system's natural frequency, causing resonance and amplifying vibrations. Pressure pulsations from the compression process may also contribute to this spike. At 1900 RPM, the system moves out of the resonance zone, reducing vertical vibrations. This behavior reflects the swash plate compressor's operating dynamics.

According to Cingiz et al. (2021) compressor vibrations increase with the use of different types of refrigerants, but changes in refrigerant levels do not significantly impact vibration. The results align with the authors' findings, indicating that varying refrigerant levels produce different vibration values under each condition. However, these changes are neither gradual nor consistent, but rather reflect fluctuations in vibration intensity. Refrigerant levels affect vibration inconsistently, causing both increases and decreases, even at normal levels, due to pressure fluctuations within the system. These fluctuations create unbalanced forces and dynamic interactions, leading to irregular vibration behavior that does not follow a predictable pattern.

4.7 Relationship of Temperature Under Different Refrigerant Condition with RPM

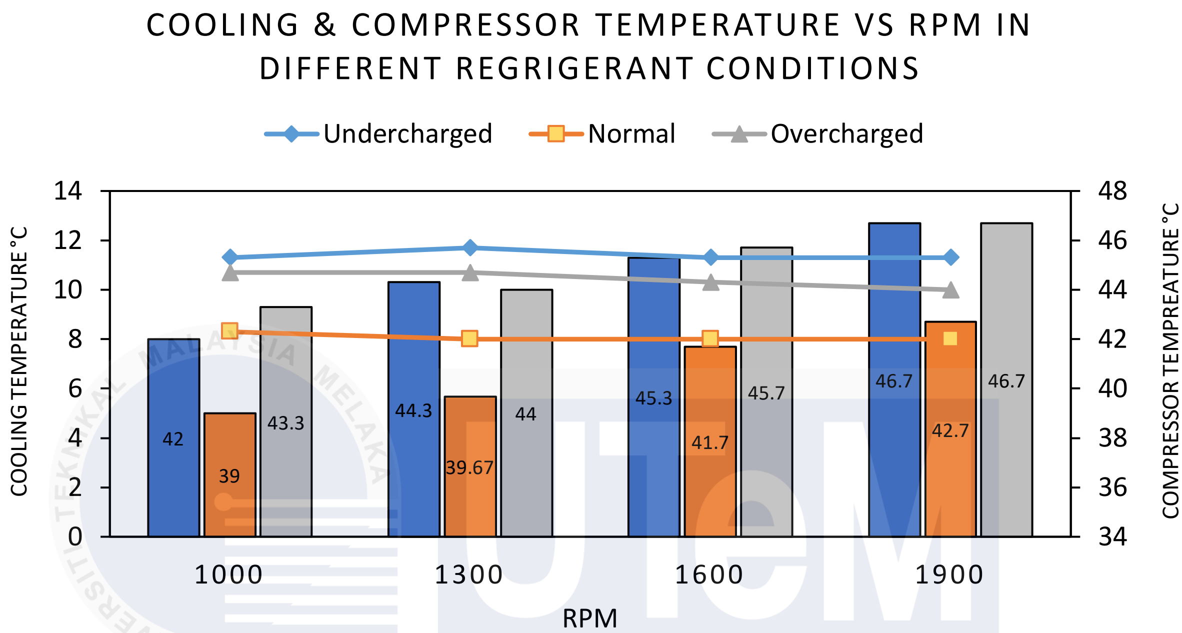


Figure 4.7 Cooling and compressor temperature versus RPM in different refrigerant condition

Figure 4.6 the cooling temperature, represented by the line graph, shows under the undercharged condition, the cooling temperature remains at approximately 12°C across all RPMs, indicating minimal variation. For the normal condition, the cooling temperature stays consistent at around 8°C, demonstrating optimal or maximum cooling performance. Under the overcharged condition, the cooling temperature is then steady at approximately 11°C, slightly higher than in the normal condition but still effective.

Furthermore, the compressor temperature, shown in the bar graph, varies significantly between refrigerant conditions. Higher RPM increases the speed of moving components, such as pistons or swash plates in the compressor. This leads to greater friction between moving parts, producing additional heat, which raises the compressor temperature. According to the ideal gas law, as pressure rises, the temperature of the compressed refrigerant also increases, contributing to higher compressor temperatures.

The data highlights that the normal condition refrigerant achieves the lowest cooling temperature and maintains stable compressor operation with minimal overheating. In contrast, both the undercharged and overcharged conditions result in higher compressor temperatures, indicating increased operational strain. Additionally, RPM has a noticeable impact on compressor temperature in all condition, while cooling temperature remains largely unaffected by RPM. This emphasizes the importance of maintaining the correct refrigerant level for optimal system performance. According to Deymi-Dashtebayaz et al. (2018) this align with the current results from Figure 4.11 that the author stated the lack of appropriate refrigerant mass charge causes the refrigeration system not to reach its maximum cooling capacity.

4.8 Verification of Analysis Results

To ensure the analysis is reliable and comparable, the data results were verified using the reference shown in Figure 4.7, based on Bonifaccino (2020). The data indicates that the optimal cooling temperature in a 25°C ambient environment should achieve 10°C. However, both the CAECT and the alternative test rig demonstrated a maximum efficiency of 8°C, aligning with the performance standard for R134a refrigerants. This finding validates that the compressor and refrigerant levels were operating within their designed specifications, confirming the system's ability to deliver the expected cooling performance under normal conditions. These results reinforce the importance of maintaining appropriate refrigerant and oil levels in achieving maximum cooling efficiency.

Ambient Air Temperature	Relative Humidity	Service Port Pressure		Maximum Left Center Discharge Air Temperature
		Low Side	High Side	
13–16°C (55–65°F)	0–100%	175–206 kPa (25–30 psi)	340–850 kPa (49–123 psi)	7°C (45°F)
19–24°C (66–75°F)	Below 40%	175–215 kPa (25–31 psi)	430–930 kPa (62–135 psi)	6°C (43°F)
	Above 40%	175–254 kPa (25–37 psi)	570–1070 kPa (83–155 psi)	9°C (48°F)
25–29°C (76–85°F)	Below 35%	175–249 kPa (25–36 psi)	760–1410 kPa (147–205 psi)	9°C (48°F)
	35–60%	175–261 kPa (26–38 psi)	830–1180 kPa (120–171 psi)	10°C (50°F)
	Above 60%	185–286 kPa (27–42 psi)	880–1250 kPa (128–181 psi)	11°C (52°F)
30–35°C (86–95°F)	Below 30%	193–293 kPa (28–43 psi)	1010–1410 kPa (146–205 psi)	12°C (54°F)
	30–50%	228–269 kPa (30–44 psi)	1050–1440 kPa (153–209 psi)	13°C (55°F)
	Above 50%	221–324 kPa (32–47 psi)	1100–1470 kPa (160–213 psi)	14°C (58°F)
36–41°C (96–105°F)	Below 20%	241–337 kPa (35–47 psi)	1310–1700 kPa (190–246 psi)	16°C (61°F)
	20–40%	247–345 kPa (36–50 psi)	1320–1700 kPa (190–230 psi)	16°C (61°F)
	Above 40%	259–353 kPa (37–52 psi)	1350–1690 kPa (196–246 psi)	16°C (61°F)
42–46°C (106–115°F)	Below 20%	292–378 kPa (42–55 psi)	1630–1950 kPa (238–283 psi)	17°C (62°F)
	Above 20%	297–383 kPa (43–55 psi)	1620–1930 kPa (235–280 psi)	19°C (66°F)
47–49°C (116–120°F)	Below 30%	338–405 kPa (50–59 psi)	187–2080 kPa (271–302 psi)	20°C (68°F)

Figure 4.8 R-134a refrigerant performance chart (Bonifaccino, 2020)

4.9 Results Summary

The development of the Car Air-Conditioning Electrical Compressor Test Rig (CAECT) was aimed to create a portable and efficient system for educational and analytical purposes. Featuring key components like an electric scroll compressor and R134a refrigerant, the test rig successfully measured critical parameters on various point sensor using data logger and pressure sensor, achieving a high Coefficient of Performance (COP) of 5, surpassing typical air-conditioning systems.

Furthermore, experimental results showed RMS vibration increasing with RPM, while refrigerant levels caused inconsistent vibration changes and affect variable temperature. Notably, optimal cooling performance recorded at 8°C for both developed and alternative test rig under normal refrigerant levels aligned with R134a standards. Validation tests confirmed reliability, making the CAECT an effective tool for technical training and performance analysis.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Summary of Test Rig Development

In conclusion, the objectives of this study were successfully achieved through the development and testing of the air-conditioning compressor test rig. The first objective, to develop the test rig was accomplished by successfully creating a functional platform capable of simulating real-world automotive air-conditioning systems for laboratory learning from output data of the system with a COP of 5 means the system delivers 5 units of cooling for every 1 unit of electrical energy consumed, indicating exceptional efficiency.

The test rig is equipped with key components, including an electric power supply to operate the compressor, strategically placed thermocouples at various points to monitor temperatures, and a control system for adjusting operational conditions and refrigerant levels. This setup enables comprehensive experimentation by allowing variations in refrigerant charge providing valuable insights into their impact on system performance.

5.2 Summary of Analysis

The second objective, to study the relationship of different refrigerant with different RPM affecting vibration level and temperature for laboratory purpose was also achieved using an alternative test rig and online vibration monitoring. This approach was necessary due to limitations encountered during the development phase of the primary test rig.

Referring to Table 5.1 the most influential parameter on vibration is RPM, with higher RPM increasing vibrations and compressor temperature due to higher pressures as described by the ideal gas law, though it does not affect cooling temperature. Refrigerant level impacts both cooling and compressor temperatures with also affecting vibration but inconsistently, causing it to either increase or decrease depends on quantity applied. Lasty, the horizontal and vertical axis vibrations are critical parameters to monitor for effective performance analysis of a swash plate compressor.

Table 5.1 Summarize of data analysis

Parameter	Effect on Vibration	Effect on Temperature	Remarks
RPM	The primary parameter influencing vibration, higher RPM results in increased vibrations.	Higher RPM compresses refrigerant to higher pressures, increasing compressor temperature (ideal gas law). Not effecting cooling temperature	Most significant factor in vibration and compressor temperature behavior.
Refrigerant Level	Affects vibration but does not show a consistent pattern of increase or decrease because of pressure fluctuations in system.	Impacts both cooling and compressor temperature, with improper levels leading to inefficiencies.	Proper levels are critical for optimal performance.
Horizontal Axis Vibration	Driven by rotational dynamics, vibrations consistently increase with RPM.	-	Reflects the orbital motion of the swash plate.
Vertical Axis Vibration	Influenced by axial forces, pressure pulsations, and resonance effects, causing non-linear behavior.	-	More sensitive to dynamic interactions and resonance.

5.3 Limitations of the Research

This research encountered several limitations that influenced the scope and methodology of the research. Due to time constraints and lack of knowledge and experience during the development phase, the primary test rig was unable to incorporate and included 3 types of compressor instead the final development student used only one type of compressor.

Furthermore, the feature for RPM changes into the CAECT could not be implemented also due to time constraints and limited knowledge. Additionally, the study relied on an alternative test rig to gather experimental data on cooling performance, compressor temperature, and vibration behavior, as the developed test rig was not fully operational for different RPM on compressor, but it can operate very well as a normal air conditioning vehicle system.

5.4 Future Recommendations

The development of the test rig should prioritize the integration of RPM adjustment feature. This will allow for detailed monitoring of refrigerant flow dynamics and temperature variations under varying compressor speeds, providing a comprehensive understanding of the system's performance. Furthermore, this enhancement would enable direct analysis of the CAECT system itself without relying on an alternative test rig.

Next, future analysis should test with different refrigerants to assess their impact on electric scroll compressor vibration and performance. Additionally, varying oil levels in the scroll compressor also should be analyzed to determine their effects on cooling efficiency, vibration, and temperature using the CAECT.

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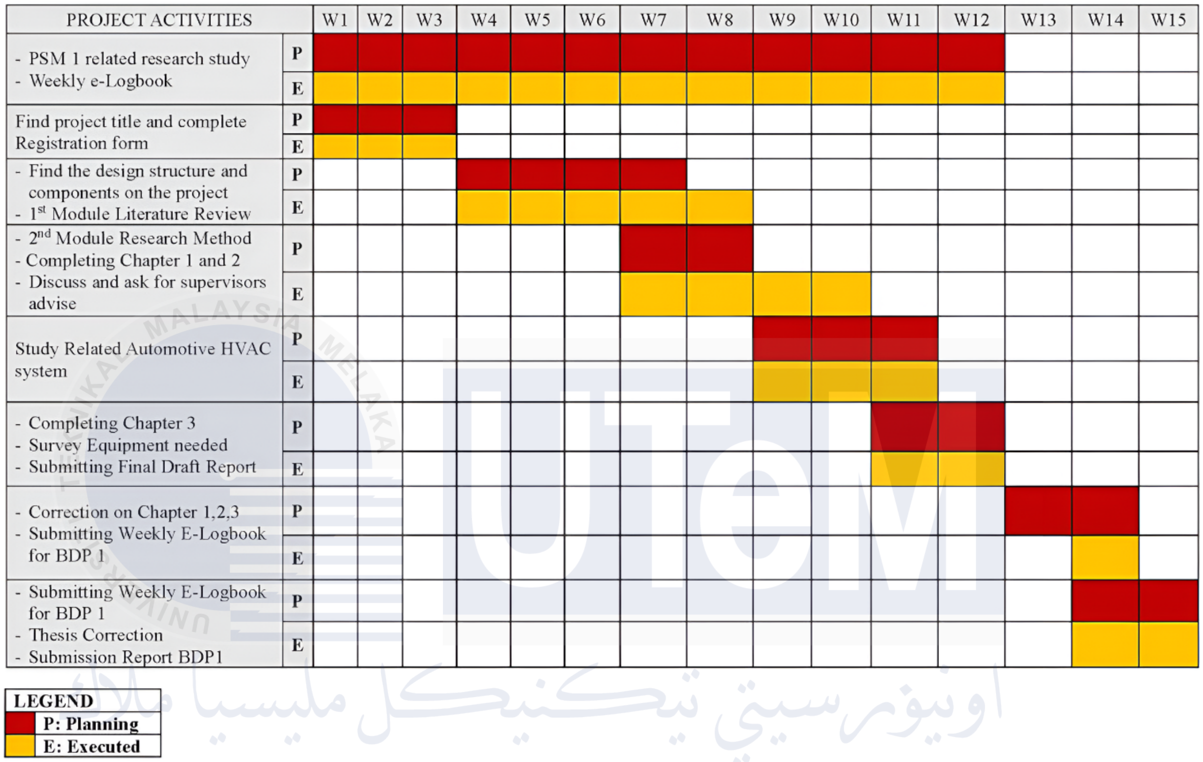
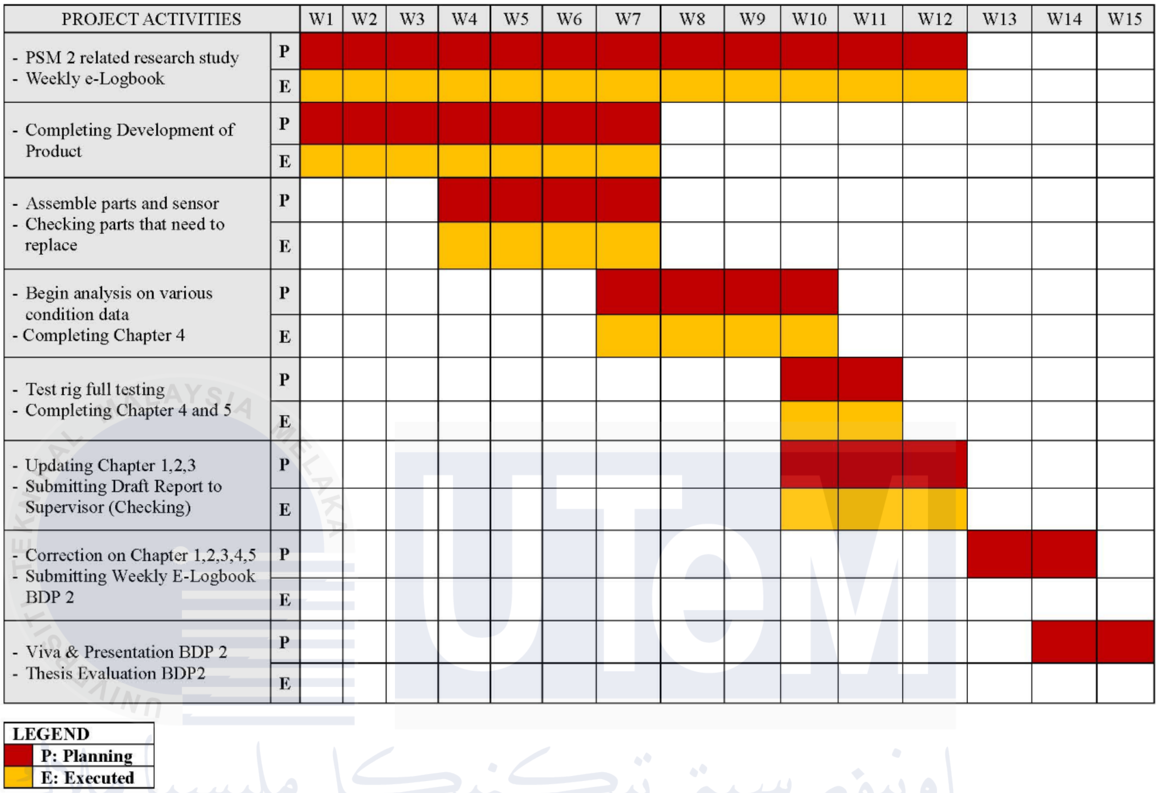
APPENDICES

APPENDIX A Project Gantt Chart 1



APPENDIX B Project Gantt Chart 2



APPENDIX C ISO 10816 (Vibration Severity)

VIBRATION SEVERITY PER ISO 10816

Vibration Velocity Vms In/s	mm/s	Class I Small Machines	Class II Medium Machines	Class III Large Rigid Foundation	Class IV Large Soft Foundation
0.01	0.28	GOOD	GOOD	GOOD	GOOD
0.02	0.45	GOOD	GOOD	GOOD	GOOD
0.03	0.71	GOOD	GOOD	GOOD	GOOD
0.04	1.12	SATISFACTORY	GOOD	GOOD	GOOD
0.07	1.80	SATISFACTORY	SATISFACTORY	GOOD	GOOD
0.11	2.80	UNSATISFACTORY	SATISFACTORY	SATISFACTORY	GOOD
0.18	4.50	UNSATISFACTORY	UNSATISFACTORY	SATISFACTORY	SATISFACTORY
0.28	7.10	UNACCEPTABLE	UNSATISFACTORY	UNSATISFACTORY	SATISFACTORY
0.44	11.2	UNACCEPTABLE	UNACCEPTABLE	UNSATISFACTORY	UNSATISFACTORY
0.70	18.0	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	UNSATISFACTORY
0.71	28.0	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE
1.10	45.0	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE

APPENDIX D Electric Scroll Compressor Specification

Refrigerant (Gas): R134a
Speed range: 1000～3100 rpm
Working pressure: Suction pressure: 0.2～0.45Mpa
Discharge pressure: ≤2.0Mpa / ≤2.2Mpa
pressure ratio: ≤10 Ambient
temperature: -40℃ - 80℃
Discharge temperature: ≤110℃
Lubricating oil require: 8%-10% of whole system refrigerant (Gas)

Compressor data:
Compressor style: Semi-closed Horizontal Scroll
Compressor Material: Aluminum alloy Voltage: DC 12V / 24V
Working voltage range: 10.5VDC～15VDC / 19.5VDC～32VDC
Current: 45A+-2 / 35A+-2
Displacement: $21cm^3/r$
Cooling capacity: 1.688KW / 2.465KW (5731BTU / 8410BTU)
Speed range: 1000 - 2300rpm / 1000 - 3000rpm
Rated power: 550W / 850w Rated speed: 1800rpm / 3000rpm
Oil: POE / 130ml - 150ml (Oil has already in compressor)
Gas/Refrigerant: R134a
Condensing temperature range: 26.7～68℃
Evaporating temperature range: -10～12.5℃
Refrigerant leakage rate: <14g per year
Suction pipe inner size: Ø18.3mm
Discharge pipe inner size: Ø15.5mm COP W/W: 3.07 / 2.9
Compressor body not to be tilted (the angle between the main axis of the compressor and the horizon should not be greater than 5 °)

Brushless controller unit :
Brushless direct current controller
1. Over / Under voltage protection: DC 12V -- (21V / 10.5V) DC 24V -- (42V / 20.5V)
2. Max power: 600w / 1200W

Generator (battery) request :
12V compressor require generator ampere over 100A;
24V compressor require generator ampere over 70A.

About vehicle battery. If you want to use the electric compressor after parking, then your vehicle battery capacity should be large enough. For example, 12V compressor current about 45A. So one new and full charged 45A battery can run the compressor for one hour.

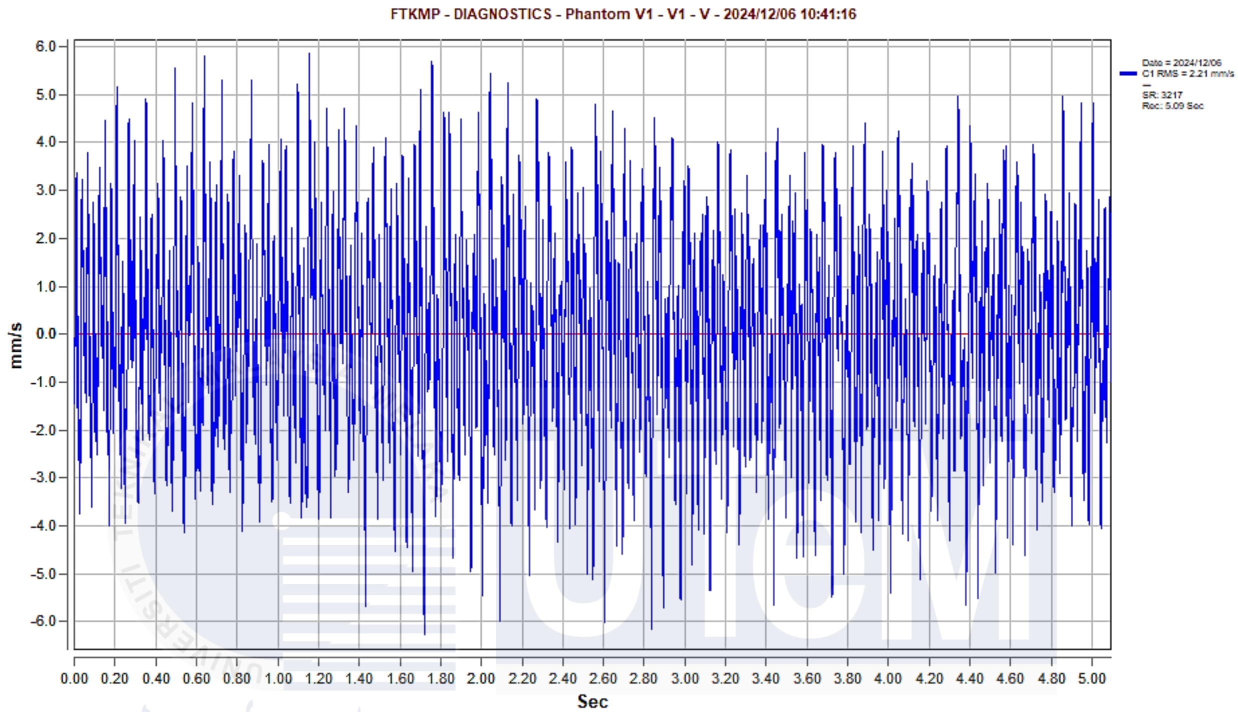
Led blinking:

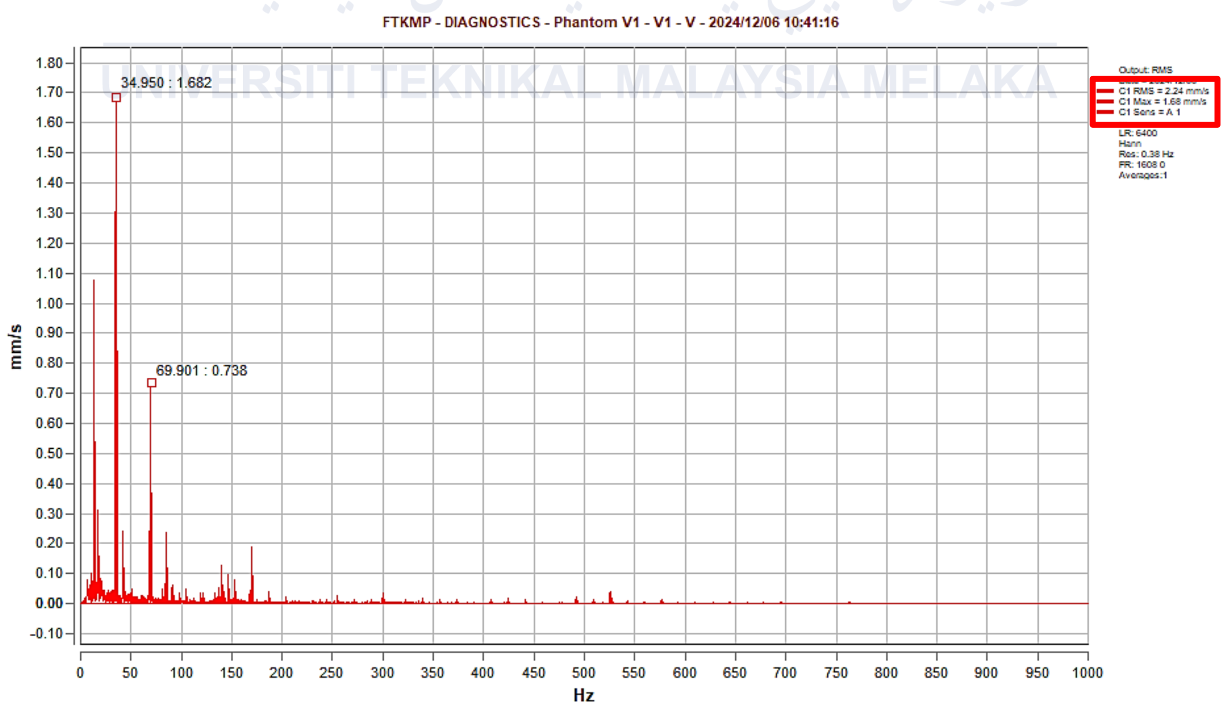
Blinking 1 times, pause 1 second: Standby mode.
Fast blinking 2 times, pause 1 second: Excessive current, Over 50A.
Fast blinking 3 times, pause 1 second: Locked rotor protection.
Fast blinking 4 times, pause 1 second: Undervoltage protection.
Fast blinking 6 times, pause 1 second: Electric fan fault.
Fast blinking 7 times, pause 1 second: Motor lack of phase. Please check if the motor got burnt and connection is correct or not.
Fast blinking 8 times, pause 1 second: Compressor over heated protection.
Fast blinking 9 times, pause 1 second: Pressure switch protection.

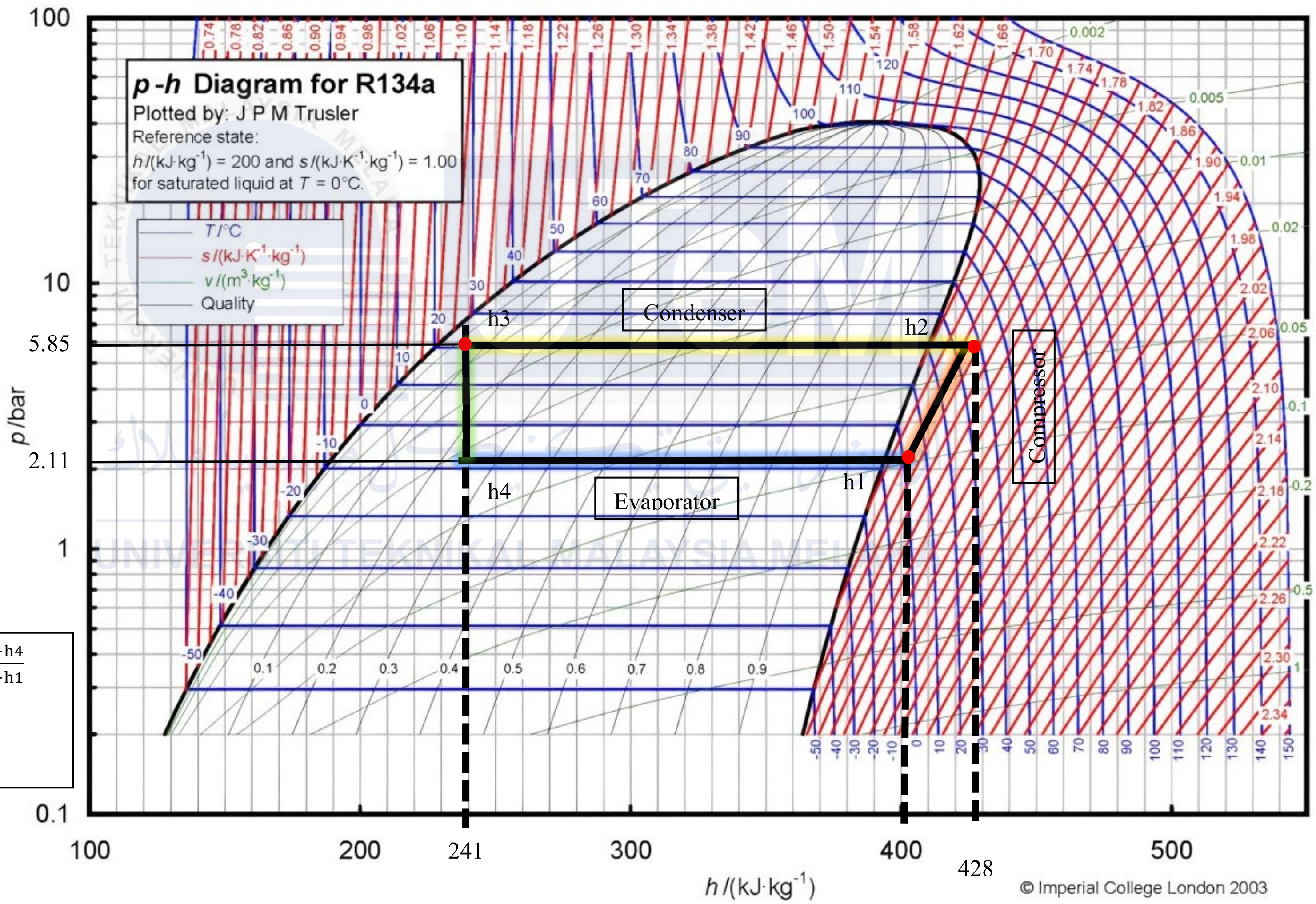
Package product list:

1. 1 x Compressor
2. 1 x Brushless controller unit
3. 1 x Power wire
4. 1 x Evaporator wire
5. 1 x Cooling fan extension lines
6. 1 x Direr (Pressure switch extension lines)

APPENDIX E RMS Vibration Results from Online Monitoring Software for Horizontal Axis in 1000 RPM







$$\text{COP} = \frac{\text{Qin}}{\text{W}} \text{ or } = \frac{\text{h1}-\text{h4}}{\text{h2}-\text{h1}}$$

$$= \frac{400-241\ (\text{KJ/kg})}{435-400\ (\text{KJ/kg})}$$

$$\text{COP} = 5$$

BDP 2_REPORT_CAR AIR-CONDITIONING ELECTRICAL COMPRESSOR TEST RIG (CAECT).pdf

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