DESIGN OF A PISTON COMPRESSOR TEST DEVICE FOR VISUALIZATION AND LEARNING OF COMPRESSOR WORKING SYSTEMS

[1]Dedy Efendy,[*2]Desmarita Leni,[3]Muchlisinalahuddin
[4] Ilham Alghani,[5]Yuni Vadila,[6]Reyhan Stevano

[1,2,3,4,6]Mechanical Engineering, Engineering, Universitas Muhammadiyah Sumatera Utara, Indonesia
[5]Mechanical Engineering, Engineering, Universitas Negeri Padang, Indonesia

Author's email:
[1]dedyefendy63@gmail.com; [2]desmaritaleni@gmail.com; [3]muchlisinalahuddin.umsumbar@gmail.com
[4]Ilhamalghani11098@gmail.com; [5]yunifadilabkt@gmail.com; [6]reyhanstevano55@gmail.com

**Corresponding author: desmaritaleni@gmail.com*

Abstract. *Piston compressors are a type of compressor widely used in industry, but students' understanding of their work cycle is often limited to theory and animation media. This study aims to design a piston compressor test rig as an interactive learning medium to visualize the suction, compression, and exhaust processes in real time. The methods used include needs analysis, three-dimensional modeling with CAD software, and design evaluation based on functionality, ergonomics, and safety aspects. The design results show the device consists of a compressor unit, a drive motor, an air tank, a 40x40 mm hollow steel frame, and an instrument panel. This configuration allows direct observation of the compressor's work cycle, with compact dimensions and modular nature for further development. Validation with three previous studies confirms the design's relevance to modern test rig trends. This device is expected to support effective learning of mechanical engineering practicums.*

Keywords: *CAD design, Learning media, Piston compressor, Test equipment, Work cycle visualization.*

1. INTRODUCTION

Piston compressors are one of the most widely used types of compressors in various industrial sectors, including the automotive industry as a power supply for pneumatic systems, the manufacturing industry to support compressed air-based production processes, and refrigeration and HVAC (Heating, Ventilation, and Air Conditioning) systems that require a certain pressure of air supply. The advantage of piston compressors lies in their ability to produce high-pressure air with a relatively simple mechanical design and a good level of efficiency in certain applications. (Nugroho et al., 2022) The working principle of a piston compressor, which involves the stages of the intake, compression, and discharge processes, is a fundamental concept that is very important for mechanical engineering students to understand. This understanding is essential because it is closely related to the application of the laws of thermodynamics, fluid mechanics, and dynamics of mechanical systems in real applications. However, learning about the compressor work cycle in academic environments is generally still limited to the delivery of theory through textbooks or digital animation-based media, which are abstract and often unable to comprehensively represent real phenomena (Syamsuri, 2023).

The urgency of this research arises from the increasing demand for qualified engineering graduates who not only understand theory but also possess practical and analytical skills in complex mechanical systems. Limited laboratory facilities providing piston compressor test equipment as a practical learning medium are one of the obstacles to achieving this competency. (Nugroho et al., 2022). Furthermore, the development of Industry 4.0 technology, which emphasizes the integration of the physical and digital worlds, demands more applicable, interactive, and realistic learning media. Therefore, the development of this test device is a strategic step to bridge the gap between theory and practice, as well as an innovation in providing engineering education facilities that are relevant to the needs of the times (Arvianto & Ardhana, 2020).

In order to overcome these limitations, it is necessary to design a test device that is capable of directly visualizing the working mechanism of a piston compressor. (Yusuf et al., 2019). This device is expected to function not only as a practical medium that allows students to observe the mechanical movement of the piston and air flow in the system, but also as an interactive learning tool that can improve understanding of the relationship between theoretical principles and physical phenomena that occur. The presence of this test device is believed to be able to provide a more applicable and realistic learning experience, so that it can strengthen students' competence in analyzing the performance of the compressor system and understanding the operational parameters that affect its performance (Agus Sudarmanto, 2017).

This research aims to design and develop a piston compressor test device that allows for real-time visualization of the work cycle in a mechanical engineering laboratory environment.(Putra et al., 2019)The device design is carried out by paying attention to aspects of functionality, ergonomics, and work safety, so that the resulting tool is not only effective as a learning medium but also meets safety standards for users.(Setiawan et al., 2023)The design process includes user needs analysis, three-dimensional modeling using Computer-Aided Design (CAD) software, and the preparation of technical specifications ready for fabrication . With a systematic, needs-based design approach, it is hoped that this device can make a significant contribution to supporting practical and research activities in the field of mechanical engineering (Cahyono et al., 2023).

2. LITERATURE REVIEW

2.1 Working Principle of Reciprocating Compressor

Reciprocating compressors are included in the category of positive displacement compressors which work by converting mechanical energy from shaft rotation into air pressure energy (Leni, 2024). This working process consists of three main stages, namely: (1) the suction process, when the piston moves down and air from outside enters the cylinder, (2) the compression process, when the piston moves up and the cylinder volume decreases so that the air pressure increases, and (3) the exhaust process, when the exhaust valve opens and high-pressure air is expelled from the cylinder. Variations in the working pressure value, cylinder size, valve shape, and type of drive motor can affect the engine rotation value (RPM) and working power of the reciprocating compressor (Sadiana et al., 2022).

2.2 Reciprocating Compressors in Pneumatic Applications

Reciprocating compressors are widely used in pneumatic systems because they can produce high working pressures with good efficiency. The compressed air from the compressor is used as the driving force for various pneumatic devices, such as working cylinders, control valves, and automated machines. This application makes reciprocating compressors an ideal choice for industrial applications requiring pneumatic power at high working pressures in relatively short periods of time (Nugraha et al., 2024).

2.3 The Importance of Practical Learning Media in Engineering Education

Engineering education emphasizes mastery not only of theoretical aspects but also of the practical application of the technical concepts taught. Practical learning media, such as test equipment or work simulators, can bridge this gap by allowing students to directly observe and practice the working processes of complex systems (Aqsha et al., 2024).

Previous research has emphasized that experiential learning (learning by doing) can accelerate the process of mastering material and deepen students' understanding of the working principles of mechanical and thermodynamic systems, particularly in the context of reciprocating compressors. Using this medium, students can observe work patterns, measure work parameters (pressure, volume, RPM), and make direct connections to the theoretical concepts taught (Makahinda et al., 2023).

Furthermore, practical learning media can increase student engagement, develop teamwork skills, and hone critical thinking and problem-solving skills in real-world work contexts. By facilitating hands-on experience and allowing for the visualization of complex work processes, these media can be used as a more comprehensive instrument for evaluating student competency than purely theoretical examination methods (Mukarima et al., 2024).

2.4 Needs and Challenges in Developing Learning Tools

Developing practical learning tools requires careful consideration to ensure their efficient use in both academic and practical contexts. Some requirements to consider include suitability to learning objectives, the ability to visualize complex work processes, the level of interactivity for learners, the existence of a measurement and evaluation system that can quantify work parameters, and simplicity of operation (Dwi Ermawati & Kurniawan, 2019).

However, the development of these learning tools also faces various challenges, including resource and budget constraints, the complexity of device design, and the need to adapt tools to different curricula and academic needs. Budget constraints can hinder the implementation of fully featured technology, while design complexity requires collaboration with experts and industry to produce tools that are accurate, efficient, and relevant to learning and workplace needs (Ulya et al., 2023).

3. RESEARCH METHODS

This research is engineering research with a design and development approach, which aims to design and realize a reciprocating compressor test tool as a visualization and learning medium for the compressor working system. The research stages include literature studies, identification of user needs, design planning with CAD software, mechanical work simulation, prototype creation, to testing and evaluation of tool performance. The entire research process was carried out at the Mechanical Engineering Laboratory, Mechanical Engineering Study Program, Muhammadiyah University of West Sumatra, Padang City, from May to July 2025. A flowchart explaining the sequence and interrelationship of each stage of this research is presented in Figure 1.

Figure 1. Flow chart (Source: Authors, 2025)

1. Literature Review

This research began with a literature review from various scientific sources, including journals, textbooks, and standards related to reciprocating compressor technology. This phase aimed to understand the operating principles, duty cycle, and technical parameters of reciprocating compressors, as well as to identify the visualization requirements for learning media in mechanical engineering.

2. Problem and Objective Definition

Based on the literature review, the research problem and objectives are formulated, namely the unavailability of a test tool that can visualize the working cycle of a reciprocating compressor in a realistic and educational manner. The purpose of this research is to design and develop a reciprocating compressor test tool that can be used as a visualization and learning medium for students, in order to bridge the gap between theoretical understanding and practical experience.

3. Design and Development

This stage includes the design and development of test equipment using Computer-Aided Design (CAD) software. The equipment design is developed to demonstrate the working mechanism of a reciprocating compressor, including the piston-cylinder system, valves, and drive mechanism. Materials, pressure and volume sensors, drive systems, and control panels are also selected to ensure compliance with technical specifications and learning needs.

4. Initial Testing

After the design is complete, an initial testing phase is conducted to ensure the device performs as intended. This testing includes checking piston movement, valve operation, initial pressure and volume measurements, and checking the safety and stability of the device's operating system.

5. Final Testing and Evaluation

At this stage, final testing and evaluation of the test equipment's performance are conducted to verify the accuracy of the pressure and volume sensors, the visualization of the work process, and the ease and safety of user operation. The evaluation also includes testing the equipment's effectiveness as a learning tool using pre-tests, post-tests, and questionnaires to gauge students' understanding and practical experience.

6. Conclusions and Recommendations

This study concludes with a conclusion regarding the successful design and development of a reciprocating compressor tester as a learning tool. Based on the testing and evaluation results, it can be seen to what extent this tool can be used to support students' mastery of the working concepts and operational characteristics of reciprocating compressors. Furthermore, recommendations are also presented for further development, including design improvements, the addition of visualization features, and the implementation of more sophisticated sensor technology and control systems to maximize the benefits of this tool in academic and industrial contexts.

4. RESULTS AND DISCUSSION

4.1 Discussion

4.1.1 Design of Piston Compressor Test Device

The design results of the piston compressor test device are presented in the form of a three-dimensional (3D) model created using Solidworks 2024 Computer-Aided Design (CAD) software. This model aims to provide detailed visualization of the entire system before the fabrication stage, while ensuring that the dimensions and configuration of the components have met the functional and ergonomic requirements. The resulting design shows a systematic arrangement of the main components to facilitate the assembly process, operation, and observation activities when used as a learning medium in the laboratory.

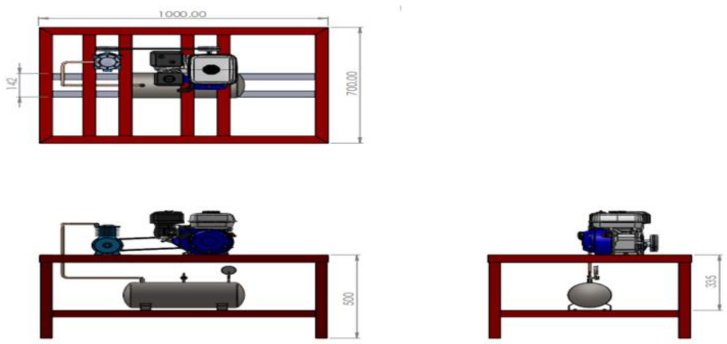

Figure 2. Compressor design (Source: Authors, 2025)

This test device consists of several main components as follows:

1. Piston Compressor Unit This unit is the core of the system, which functions to suck in atmospheric air, then compress it to a certain pressure before being distributed to the storage tank. The piston compressor was chosen because of its simple and easy-to-visualize mechanism, making it suitable for educational purposes. The reciprocating motion of the piston inside the cylinder can be directly observed, allowing students to understand the stages of the suction, compression, and exhaust cycles.

2. Drive Motor The drive motor is mounted on the upper platform of the frame and serves to provide mechanical power to the compressor through an integrated transmission mechanism. The choice of position above the table is designed to facilitate maintenance, inspection, and operation. Furthermore, this placement minimizes the risk of vibration that could affect the overall stability of the system.

3. Air Tank The air tank is placed under the table surface and serves as a reservoir for compressed air. Placing the tank at the bottom aims to keep the device's center of gravity low, thus increasing the stability of the structure during operation. The tank is also equipped with a specially designed stand to withstand dynamic forces resulting from fluctuations in air pressure.

4. Support Frame The frame structure is made of hollow steel profiles with a square cross-section, which are coated with red paint to increase corrosion resistance and provide an aesthetic impression. The cross-sectional dimensions and frame configuration have been adjusted to support the load of the compressor, motor, and air tank with a certain safety factor. In addition to being a structural element, the open frame design also functions to make it easier for students to observe the system's working process from various directions.

5. This panel is equipped with a pressure gauge that monitors the air pressure in the tank in real time. This instrument panel allows users to obtain visual data regarding the compressor's operating conditions, which is important for practical purposes and performance analysis.

The overall dimensions of the test frame are 1000 mm x 700 mm x 500 mm, with a table height of 500 mm adjusted to user ergonomics. This size is designed to be compact enough to be placed in a laboratory space without interfering with movement around it. In addition, the proportional table height allows students to observe the mechanical movement of the piston and air flow from an optimal viewing angle, without requiring a burdensome body position.

4.1.2 Design Analysis

This piston compressor test rig is specifically designed to support the learning process through realistic visualization of the system's working mechanisms. One key aspect of the design is that it allows users to directly observe the piston movement during the intake, compression, and exhaust cycles. This visualization is crucial for mechanical engineering students to understand the relationship between thermodynamic theory and the mechanical phenomena that occur in piston compressors. The compressor unit's placement on top of the table was deliberately chosen to provide wider viewing access. With this position, students can make unobstructed observations of the movement of mechanical components and the resulting airflow, both from the front, sides, and top of the device. Furthermore, the use of an open frame design allows for optimal natural and artificial lighting to enter the compressor work area, allowing component details to be more clearly visible during the practicum.

In terms of stability, the air tank's placement under the table is strategically designed to keep the system's center of gravity lower. This configuration not only improves the device's stability during operation but also reduces the risk of excessive vibrations caused by the dynamic movement of the drive motor and compressor. This significantly reduced vibration is crucial for both the safety of the device and user comfort during the lab.

The choice of frame material is a crucial aspect of the design analysis. Hollow steel with a square cross-section measuring 40 mm x 40 mm was chosen because it has a good strength-to-weight ratio, so it can effectively support the dynamic loads from the drive motor, compressor, and air tank. Hollow steel is also known to have adequate structural stiffness for such applications, thus minimizing deformation when the device is operating under full load conditions. Furthermore, hollow steel is readily available in the market and relatively economical, thus in accordance with design principles that consider aspects of material availability and manufacturing costs.

Additional consideration was given to the method of connecting the frame components. Welding was chosen as the primary fastening method because it provides high-rigidity joints, which are necessary to withstand the dynamic forces and vibrations generated during device operation. Welded joints also offer aesthetic advantages, producing a neater, more seamless connection compared to bolts and nuts. Maintaining frame rigidity improves the overall stability of the system, thus enhancing user safety and comfort during laboratory use.

4.1.3 Design Excellence

This piston compressor test rig design offers several advantages that make it innovative and relevant as a learning tool in mechanical engineering laboratories. These advantages include visualization, compact and ergonomic dimensions, and a modular nature that allows for further development.

a. Real Visualization

One of the main advantages of this design is its ability to provide a realistic visualization of the piston compressor operating cycle. With its open-frame configuration and strategic component placement, students can directly observe the mechanical motion of the piston, the inlet and outlet airflow, and the interactions between components during the intake, compression, and exhaust cycles. This provides significant added value to the learning process, as students not only understand the concept theoretically but also can directly observe the physical phenomena that occur. Real-world visualizations like this have proven to be more effective in improving students' conceptual understanding and analytical skills, in line with the practice-based learning approach (experiential learning).

b. Compact and Ergonomic

The device is designed with total dimensions of 1000 mm x 700 mm x 500 mm, which is considered compact by educational laboratory standards. This size allows the device to be easily placed in the lab room without disrupting the workflow or mobility of surrounding users. Furthermore, the table height of 500 mm has been adjusted to meet ergonomic principles, so students can observe and interact with the device in a comfortable body position. This ergonomic consideration is important to prevent fatigue or the risk of injury during long lab sessions.

c. Modular and Adaptive

Another advantage of this design is its modular nature. The frame configuration and separate component placement allow for easy disassembly and reassembly. This opens up opportunities for further development and modification, such as the addition of pressure sensors, temperature sensors, or an IoT (Internet of Things)-based monitoring system in the future. With this adaptability, the device not only serves as a basic learning tool but can also be used as a research platform for more in-depth testing of piston compressor performance parameters. This design flexibility supports the future-proof concept, where the device can be continuously updated according to technological developments and curriculum needs.

4.2 Design Validation

The design of this test rig demonstrates strong alignment with findings from state-of-the-art research in the field of compressor systems and test rigs, particularly in terms of visualization, modularity, and integration of measurement instruments.

First, a study by Marzouk et al. (2025) on the construction of a small reciprocating compressor-based vacuum device highlights the importance of an easily observable design connected to laboratory elements for demonstrating thermodynamics and fluid mechanics concepts. Like their rig, your test device emphasizes direct observation with an open frame and platform that allows students to easily observe the suction, compression, and exhaust cycles, supporting an applied learning approach.

Second, a two-stage test rig for reciprocating compressors from the Efficiency and Performance Engineering Network (2020) assembled a complete sensor suite (pressure, temperature, vibration) on a modular compressor system with a top motor, bottom tank, and belt transmission. This structure faced the challenges of dynamic loads and instrument integration. Your design applies similar principles: the compressor unit on the top platform, the bottom tank for stability, and the real-time instrument panel as a modular element. The choice of 40x40 mm hollow steel and welding methods strengthens the structure against dynamic loads and vibrations, like the methods used to increase rigidity in the modular rig.

Third, research by Springer et al. (2023) on an improved hermetic compressor test rig highlights modularity and data-driven system integration (AI/ANN), where pressure sensors and fast data acquisition of up to one minute are used for high-accuracy cooling capacity inference. This underscores the need for modular systems that allow for the addition of sensors and complex data connections. Their modular design, which allows for future sensor expansion (e.g., IoT, performance prediction, AI), follows the trend of today's adaptive and data-centric rigs.

CONCLUSION

This research resulted in the design of a piston compressor test rig designed to facilitate visual learning of the compressor duty cycle. The design utilizes an open frame made of 40x40 mm hollow steel with an ergonomic and compact component configuration, facilitating observation and maintaining the stability of the tool. Analysis shows advantages in real-world visualization, modularity for further development, and readiness for sensor integration. Validation with three recent studies confirms the relevance of the design to modern test rig trends. This device is expected to improve students' practical understanding and support further research in the field of compressor systems.

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