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From Vacuum to Validation: An Advanced Simulation-Assisted Design and Development of a Sealed Components Qualification Testing System for High-Risk Industries

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Abstract

The dependability of sealed components is crucial in high-risk industries including aerospace, medicine, automotive, and defense where system integrity is crucial. A Sealed Components Qualification Testing System (SCQTS) was designed, built, and tested in this paper with the goal of assessing components in simulated extreme environmental conditions, such as pressure, vacuum, and humidity. Finite Element Analysis (FEA) and stress simulations are used to test the system's structural resilience, which includes a specially constructed sealed chamber and buffer assembly. Helium is used as a tracer gas and quantified using a mass spectrometry-based detection approach to find micro-leaks with great precision. Vacuum creation, helium pressurization, leak identification, nitrogen purging, and the safe removal of the tested component are all steps in the methodical procedure. This reduces industrial losses and improves worker protection by improving safety, performance, and early problem detection. The system supports several Sustainable Development Goals (SDGs) of the UN and has important industrial consequences. It supports contemporary testing techniques in high-tech industries and advances SDG 9 (Industry, Innovation, and Infrastructure) by guaranteeing the dependability of sealed parts. Improving operational safety, preventing breakdowns, and lowering financial losses all contribute to SDG 8 (Decent Work and Economic Growth). Making sure that manufacturing is environmentally sound is one way to fulfil SDG 12 (Responsible Consumption and Production). To sum up, this research provides a reliable, affordable, and sustainable way to test sealed components in mission-critical systems while guaranteeing performance, safety, and compliance in real-world settings.

Keywords: Controlled Chamber, Buffer, Pressure Relief Valve, Leybold Gauge, Vacuum Gauge, Tracer Gas, Helium Leak Detection

Introduction

High-reliability components for increasingly demanding environmental and mission profiles, specifically in the aerospace, automotive, and energy sectors [1]. In these applications, sealed components that shield delicate internal parts from harmful things such as dust, moisture, and varying pressures are critical [2]. If these are not functioning properly, it could mean a very costly repair bill, a safety risk, or even worse [3]. Robust qualification testing of each component in its expected operational condition is therefore essential to avoid reliability and safety issues [4]. This demand led to SCQTS which meets the needs of testing sealed parts in greater depth. This system tests the strength and durability ofeach part, and the ability to prevent leaks. The process mimics actual pressure, temperature, and humidity levels in a unique chamber [5]. Additionally, if there are any leaks, the SCQTS will find them, meaning that only areas with the most sealing strength and reliable performance will be approved. Testing the durability and strength of parts often requires recreating stresses not possible in a standard testing routine so the SCQTS is a great asset in helping with this process. This system enables manufacturers and engineers to comply with stringent requirements, reduce risk of part failures, and build trust amongst customers with safe and superior quality products.

Problem Statement and Scope of the Study

In high-risk industries like aerospace and automobile sealed components are of great importance that safeguard against failure preventing safety risks and heavy repairs. Typical testing systems fail to produce such conditions which these components face in real life such as temperature, pressure fluctuations and certain leakages. This experimental test system is designed to ensure that the components fulfill all the checks required. It makes sure that the component is efficient and reliable enough to be used in its place.

The aim of this project is to design an experimental test bench that replicates real operating conditions such as temperature, pressure, and humidity. The system was designed and fabricated to test leakages and check sealing strength. Proper design and fabrication of the chamber and buffer ensured smooth working of the system. Pressure relief valves are installed to ensure safety in case of high-pressure accumulation. Experimental model fabricated, tested, and compared with industry standards. Evaluation of sealed components by this system ensured the safety of workers and nearby machinery. The installation of equipment is completed in a way that is safe and up to the standard under industry standards and codes

Project Methodology

This research employs a systematic leak detection cycle (shown in Figure 1) utilizing helium as a tracer gas. First, a vacuum is created in the chamber to remove interference. Next, the integrity of the system is examined, and helium is injected for testing. Mass spectrometry is then used to monitor the concentration of helium to precisely detect even micro-leaks. Lastly, purging and problem-rectification procedures guarantee dependable outcomes, ensuring that the system is accurate, safe, and compliant with industry requirements.

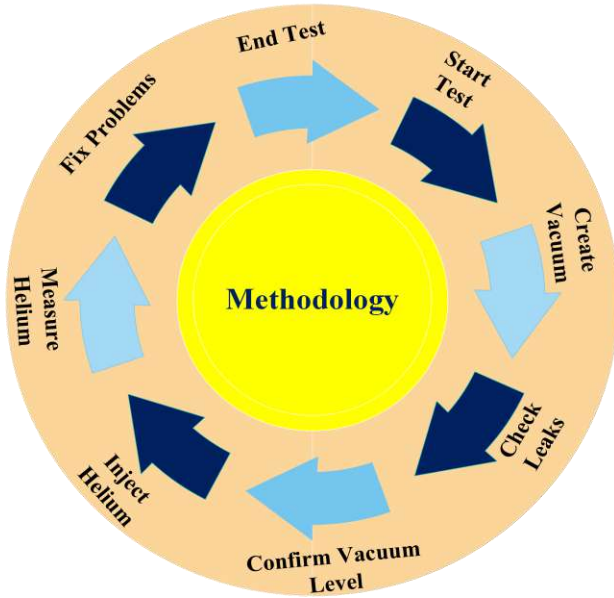


Figure 1. Working methodology of leak testing system

Selection of Tracer Gas

Tracer gas leak testing offers the best solution of leak qualification due to sensitivity, accurateness, and precision. It is a mandatory tool in businesses whose integrity or safety of systems would be threatened by anything as small as a leak. Helium the most common tracer gas because of its small atomic size which enables it to be detected using the mass spectrometry and small holes has a few merits. Also, the technique is non-toxic, non-hazardous and neutral to the environment, there will be no health hazard, and it enhances sustainability. Leak testing with the tracer gas is also time-saving and efficient in reducing the downtime as well as ensuring the maintenance of the quality of the tracer gas-leak testing is in time and this is also cost-effective. It is a familiar substitute in high-stake use as the integrity of leaks is paramount since the ability to apply it in any industry, especially the pharmaceutical and automotive sectors, and its ability to identify micro leaks. Due to its industry flexibility, as applicable to the automotive and pharmaceutical sector, and its sensitivity in responsiveness to detect micro leaks.

Working Mechanism

These steps are the foundation upon which the project approach has been based to carry out the Qualification Testing and come up with any possible seepage. Overall working of the system is illustrated in Figure 2.

1. Making Vacuum

To prepare the tracer gas leak detection method, the system will have to be powered on. All the parts and mechanisms are assembled and are available to work. The chamber and the workpiece will be evacuated to form a vacuum environment. This is an important step to remove air and other gases which may complicate tracer gas leakage detection.

2. Finding First Leak and Vacuum Check

The system is enabled to prepare the tracer gas leak detection procedure. All structures and accidents are completed and ready. The work piece and a chamber are evacuated to gain a vacuum environment. Such a process is necessitated by the removal of air and other gases which may complicate the process of seeking traces of gas leaks.

3. Check of Helium Levels and Pressurizing

The background concentration of helium and other gases are checked prior to the helium injection. This is to eliminate the occurrence of helium that may be picked up in course of the test by residue of the background level other than a leak. In the case that the background level is too high adjustments are carried out to assure proper measurement. The system under consideration contains the helium gas. It is possible to pressurize the system with helium to turn off any leakages. At this stage, the system is ready to conduct the real stage of leak inspection.

4. Reliable Leak Detection and Measurement

The amount of helium released by the workpiece is gauged by helium detector, which is usually a mass spectrometer. The highly specific separation of helium takes place using mass spectrometry where the separation occurs according to the mass-to-charge ratio of the atoms of helium. The highly sensitive method is necessary to perform accurate leak qualification because it will allow the detection of the smallest leak.

5. Removal of Helium and Nitrogen Based Cleaning

Once the detecting phase is completed, the system is evacuated one more time to get rid of residual gases, such as helium. This makes the chamber ready to the next process or maybe additional tests given the stage demands it. The chamber is purged of any residual helium or contaminants using nitrogen gas. This step guarantees that the chamber is clean and clear of tracer gas in readiness of next operation or picking of workpiece.

6. Getting the Tested Work Piece Out

The chamber cover is removed after cleaning exposing the component under test. This action almost finishes the procedure of leak identification. The process of detecting leaks is complete when the tested workpiece is removed out of the chamber. The workpiece has now been prepared to undergo additional processing or repair in case such was required based on the test outcome.

Schematic Diagram of System

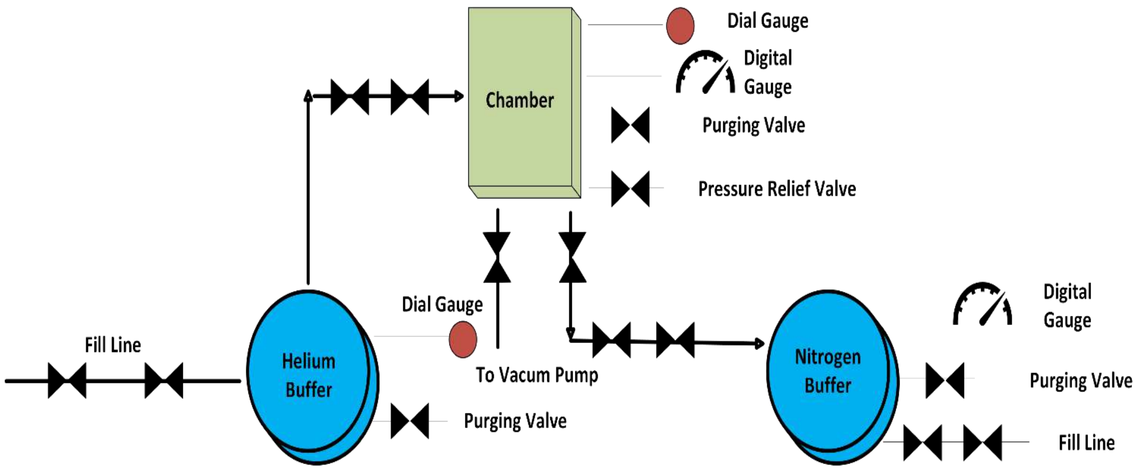


Figure 2. Schematic diagram of leak testing system

Components of System

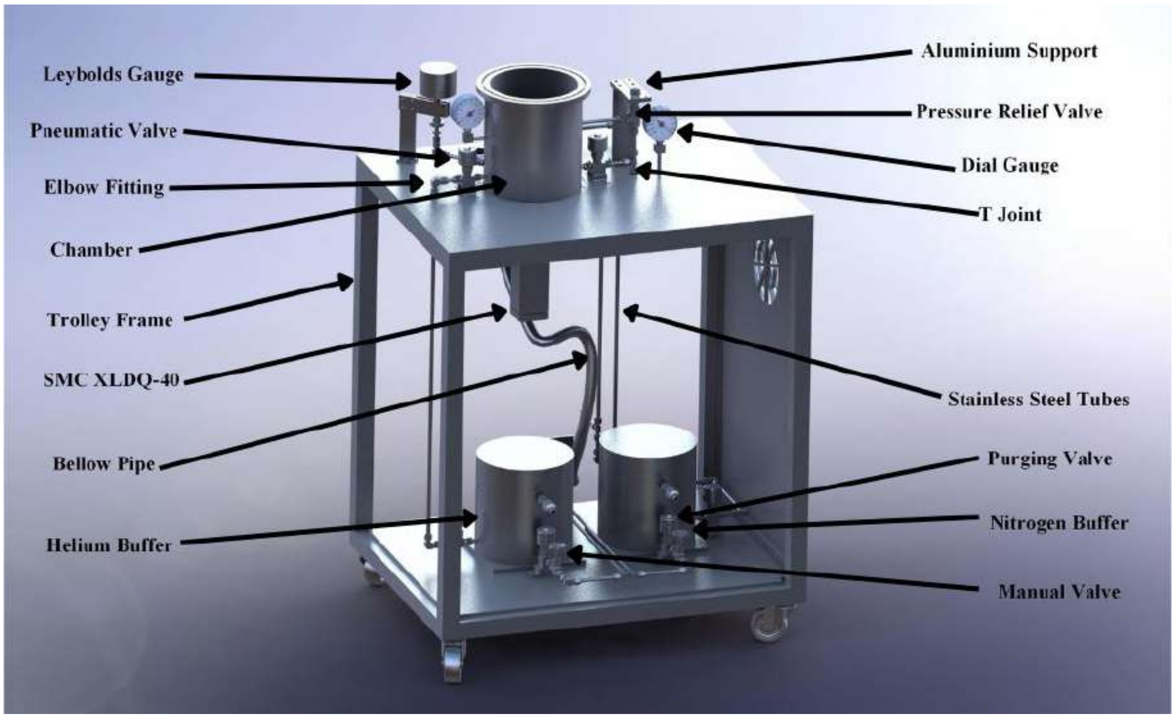


Figure 3. 3D model with system components

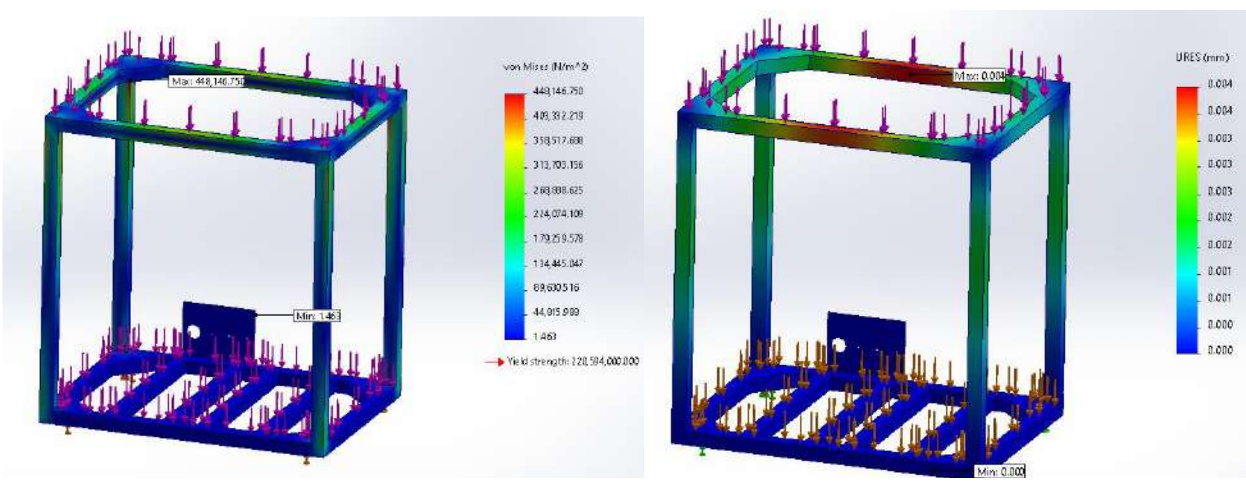
Figure 4. Fabricated model with testing facility

Fabricated Model

Each element of the system was first built up in 3D CAD software (SolidWorks) as shown in Figure 3, followed by its conversion into 2D Drawings. Figure 4 represents the real working model with complete testing facility. Raw materials were obtained in the form of stainless steel and mild steel, cut precisely and were then welded into distinct parts according to industry requirements. All the fittings such as valves, the elbows, and T-channels were tested on the level of sealing strength to ensure that there is no leakage. Appropriate piping and porting were done to ensure that all the parts were integrated into a coherent whole. More so, the development of a special designed control panel was carried out in monitoring and controlling system performance. The panel is installed with a touch control, which enables the operator to manipulate the pressure parameters and give a real-time indication on pressure and sealing strength, on the panel, therefore making the system so simple and highly productive.

Simulation Results After Load

A mild steel structure under buffer and chamber stresses was analyzed in SolidWorks simulation, showing a maximum displacement of 0.004 mm and stress of 448.15 MPa. With a yield strength of 2205.94 MPa, the theoretical factor of safety (FOS) is about 50, deliberately chosen for maximum endurance and reliability.

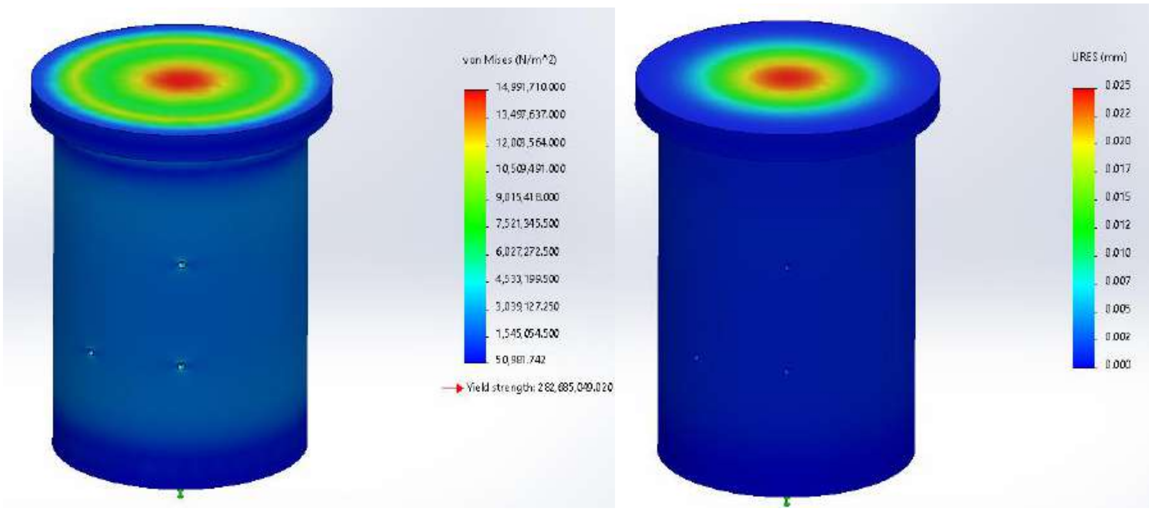


(a) (b)

Figure 5. (a) Stress results on frame, (b) Displacement values after load

Simulation Results Under Pressure on Test Chamber

A static pressure study in SolidWorks simulation was conducted on the test chamber cylinder at 0.3 MPa. Results showed a maximum displacement of 0.004 mm, maximum von Mises stress of 448.15 MPa, and a FOS of 19, confirming adequate strength for high-pressure testing.



(a) (b)

Figure 6. (a) Stress vales and (b) Displacement values after experiencing pressure

Results and Discussion

The SCQT System's integrity was validated by the pressure and structural simulation test. The frame is highly safe and can be operated without any issues, according to the frame load analysis, which showed that the highest displacement was 0.004 mm, and the stress was 448.15 MPa. This resulted in FOS above 2. A FOS of 19 was obtained by applying a pressure test to the test chamber at 0.3 MPa (3 bar), which resulted in minimum deformation (0.004 mm) and a maximum von Mises tension that is within a safety margin. These results demonstrate that the buffer and chamber can withstand more pressures and load than they are designed for. These wide safety margins enhance the system longevity, reduce the chances of leaks, and inform users that it is built to withstand high-risk industrial operations

Conclusion

The SCQTS is a dependable system of testing the integrity of sealed components in extreme environmental surroundings. It enables extremely sensitive leak detection using mass spectrometry and helium-based tracer gas detection, structures that are modelled and simulated using structural modelling and finite element analysis (FEA) to verify structural strength and safety. It allows discovering faults early leading to increased efficiency and reliability of the industries where efficiency and safety are of importance. SCQTS eliminates risk of failure, decreases timeline of certification and operator participation. This is highly adaptable and designed in a module-fashion, thus can be used in energy, automotive, aerospace, and medical applications. In general, SCQTS provides a robust, scalable, and cost-efficient means of testing high-precision components to increase the quality and safety levels of the products.

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Author Contributions

Faizan Arshad: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Muhammad Arslan**: Writing – review & editing, Data curation, Resources, Supervision**. Jawad Akhtar**: 3D Modeling, Design Refinement**. Muhammad Haseeb Khan**: 3D Modeling, Fabrication, Assembly Support. **Ahmed Sajid**: 2D & 3D Drawings, Material Preparation, Design Documentation. **Riffat Asim Pasha**: Project Administration, Supervision.

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