Design of small thermal vacuum chamber for 125-U CubeSat satellite

S. N. Ashwindran, A. A. Azizuddin*

Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Malaysia

*Corresponding author: azizuddin@ump.edu.my

Abstract. The thermal vacuum chamber is a specialized chamber to test any mechanical system, which is planned to be launched to outer space. The research is about designing a new thermal vacuum chamber to accommodate a 125-U CubeSat satellite. The role is to create a space condition environment with ultra-high vacuum in high and low temperature and induced radiation. Liquid nitrogen is utilized as the thermal medium. The proposed design is simulated and tested according to the working parameters. The velocity result indicates a sensible output velocity of 3.841 m/s with an input velocity of 10 m/s. The pressure contour provides a maximum of 13,280 Pa.

1. Introduction

In order to launch a spacecraft or any mechanical system into space, the mechanical system has to be tested in a specialized chamber called thermal vacuum chamber (TVC). The test experiment plays a significant role in validating the integrity or behaviour mechanics of the mechanical system. Thus a thermal vacuum chamber is used to study and understand the dynamic response of a mechanical system in space environment. The condition in space is extremely composed of high vacuum, radiation, varying extreme temperature etc. The dynamic processes in the solar-terrestrial system have to be analyzed before launching a hardware. Spacecraft will be directly exposed to radiation, atmospheric drag, a varying pressure and temperature, which will affect electronics, and subsystem components of the spacecraft or space-subsystem. The space environment condition can be replicated in a thermal vacuum chamber by controlling two main parameters, pressure and temperature.

TVC is guided by thermal and pressure control system, which individually controlled by many another subsystem like the fail-safe system, pressure & thermal regulation, control valve and etc. Basically, TVC has technical specification standards in order to be classified as a thermal vacuum chamber. The fundamental technical specifications are pressure and temperature controls. Pressure control system has to offer a range of high vacuum to ultra-high vacuum (1x10⁻⁶ mbar to 1x10⁻⁸ mbar) [1-4], for thermal system, the TVC has to offer a range from -190 °C to +150 °C, since the spacecraft or satellite will orbit around earth, exposing to high-temperature sunlight and low temperature during the eclipse. The quality of a thermal vacuum chamber depends on parametric value of pressure and temperature within the range set by standards and also depends on the hardware specs used to run the thermal vacuum chamber like turbomolecular pump, cryogenic pump, thermal shroud specs, cryogenic solution used, etc. The creation of vacuum can be produced by using various pumps. Commonly turbomolecular and cryogenic pump are used assisted by other subsystem [7-8].

The quality of vacuum pump depends on its specification and subsequently the quality of UHV turbomolecular pump decides the quality of the vacuum it produces. CubeSat is a type of satellite used for space research, it is measured and classified in U unit to describe the volume of a satellite.
example, 1U means the size of 10x10x10 cm [9]. There are attempts to design new thermal vacuum chamber [5], but it is an area not widely explored. The imagination of the designer is without limits. Any shape can be designed and analyzed, but one should be careful with the analysis of the results. Curved surfaces are preferable to flat panels wherever possible [6]. Generally, since TVC are huge in size, testing smaller U-Class satellites may lead to inaccurate result. Thus, designing a smaller TVC will be economical and versatile for conducting experiments and testing. Therefore the objective of the research is to design a small thermal vacuum chamber to accommodate a 125-U CubeSat satellite.

2. Methodology

2.1 Modelling of Thermal Vacuum Chamber

Design requirements study and modeling are done in accordance with the design requirements. There are 3 preliminary sketches of planned design before proceeding into the phase of finalizing a design. The designs undergo selection process which are design screening and scoring. The chosen design is the one shown in Figure 1 and Figure 2. Modeling is done in Catia V5. Subsequently, a more elaborate simulation is done to study in terms of practicality, feasibility and design requirements.

![Figure 1: Proposed thermal vacuum chamber](image1)

![Figure 2: Design of the main body](image2)

2.2 Design Requirement

Design requirement is a section of validating the motive of a design. The objective of the project is to design a unique design of TVC, with reference to the parameter mentioned in Table 1. In designing a TVC several parameters has to be considered or taken into serious consideration, failure of accounting such factor may lead to failure in numerical simulation analysis [6]. TVC is a complex equipment with an huge amount of system and subsystem. The uniqueness of the proposed TVC are the main body structure and thermal shroud design. Other subsystems are designed according to standards such as flanges, pumps, and other mechanical components involved in developing a TVC. The design focuses on the main structure and thermal shroud. Design requirement study provides an insight on the design concept of the TVC. Parameters like pressure and temperature are important in designing the TVC for structural stability, optimal heat transfer and fluid flow. In this research, the TVC is designed to provide
high vacuum with low temperature environment. In industry several types of TVC are available, providing a wide range of test service from electromagnetic interference, thermal shock, mechanical vibration, and acoustic tests [11].

**Table 1: Design Requirement**

| Parameter       | Requirement                                                                 |
|-----------------|-----------------------------------------------------------------------------|
| Size            | To accommodate 125-U CubeSat (50x50x50 cm) satellite                       |
| Pressure        | 1x10^-6 mbar [6]                                                            |
| Temperature     | Cryogenic temperature liquid nitrogen at -100 ° C                           |
| Materials       | Stainless Steel 304-L [6]                                                   |
| Manufacturing   | Ease to fabricated with current machining method                            |
| Legislation codes | Based on this directive, Standards and international code [6]            |

2.3 Thermal Shroud Design

Thermal shroud is considered as the most important element in thermal vacuum chamber. In order to fulfil the research objective which is to design a unique thermal vacuum chamber for 125-U CubeSat satellite, several options have been simulated to find an optimal design. To be as efficient as the current design, various shape and geometry has been studied to find the suitable geometry of a thermal vacuum chamber. The focus of selection criteria being used is steady state fluid flow with the constant value of velocity flow and the head loss in CFD simulation. All the design geometry are simulated under the same parameter; the best is selected as the feasible geometry of thermal shroud. Furthermore, manufacturing capabilities also must be considered prior to selecting the design. As explain previously, the concept design selection is based on scoring and given criteria. The basic criterion determined for the vacuum chamber material selection is in compliance with the established requirements, as well as the tendency to use for the type of simulation processes. There are not any specific rules or standards in the geometry shape, which describe the necessary criteria to build space simulation chamber. The pressure vessel international design standards are used as a reference. The support frame structure has been designed to maintain a high structural rigidity in order to prevent vibration caused by different sources such as pumps operation, flow of fluid and other mechanical devices connected to the chamber.

Figures 3-5 are the design of the proposed thermal shroud. Since there is no specific requirement on the geometry shape, several designs are tested to study its capabilities in fluid flow and thermal properties. Simulations are conducted to each of the design to find the best design. As shown in the Figure 4 the design of the thermal shroud pipe has an curvature domain. The current design of thermal shroud uses the concept of mode filling with liquid nitrogen in which can only be used once. The liquid nitrogen is purged out as gas by raising the temperature of the shroud of chamber above the boiling point as this is a onetime usage. The design shown in Figure 2 is based on the thermal shroud pipe system. The liquid nitrogen is passing through the pipe shroud can be cycled to the system. It requires another independent system to cool down the liquid nitrogen or to maintain the phase state.
2.4 Effect of Mesh on Result
The orthogonal quality ranges between 0-1 where the score value closer to 1 indicates a good mesh quality. Based on the mesh setup, the geometry had scored an average of 0.98, with minimum of 0.78 and maximum of 0.99 for orthogonal quality. For skewness, it has a reverse score as closer to 0 indicates a good mesh quality [10]. The proposed geometry scores an average of 0.13. The result indicates the geometry adequate simulation. A poor meshing will produce inaccurate results or a convergence error.

3. Results and Discussion
The velocity result indicates a sensible output velocity of 3.841 m/s with an input velocity of 10m/s. The pressure contour provides a result of 13,280 Pa for the maximum value, a reasonable number since the optimal pressure to maintain a liquid nitrogen in a tank ranges from 2000 - 3000 Pa. It is also noticed that the minimum pressure is -30,309 Pa. The turbulent transfer of momentum by eddy dissipation gives rise to internal fluid friction. From the simulation, the value obtained for the minimum is 2.78 x 10^-4 m^2/s^3 and for maximum the value is 32.57m^2/s^3. It is a huge difference from the value via manual
calculation which is $2.73 \times 10^{-7} \text{ m}^2/\text{s}^3$. The reason for the significant difference is because manual calculation compensate parameters to ease the calculation. For eddy viscosity, the results obtained is $2.45 \times 10^{-5} \text{ Pa.s}$ for the minimum and $93.48 \text{ Pa.s}$ for the maximum as shown in Figure 6 - 10.

![Figure 6. Laminar flow streamline](image)

![Figure 7. Transient velocity streamline](image)

![Figure 8. Transient pressure contour](image)
4. Conclusions
Design and simulation analysis has been presented with the aim of proposing a suitable and unique design of thermal vacuum chamber. The results obtained from the simulation shows that the proposed design is running well within the working parameters. As the design is in the preliminary stage, it is analyzed based on CFD numerical analysis. However, the simulation results need to be compared an experimental result to validate the design.

Acknowledgment
The authors are thankful to Universiti Malaysia Pahang for providing the necessary support for this paper under the research no. RDU170385.

References
[1] L. Westerberg, "Vacuum Technology", CERN, 1999.
[2] European Committee for Standardization, "Cryogenic vessels & static vacuum insulated vessels", 2002.
[3] C. Hauviller, "Design of vacuum chambers for experimental regions of colliding beam machines", IEEE Particle Accelerator Conference, 1993.
[4] Pressure Vessel Design Handbook, Krieger Publishing Company, 1993.
[5] Sanjay Jayaram and Eliu Gonzalez, "Design and construction of a low-cost economical thermal vacuum chamber for spacecraft environmental testing", 2009.
[6] C. Hauviller, "Design rules for vacuum chambers", CERN, 2000.
[7] Introduction to high and ultra-high vacuum production, Pfeiffer Vacuum, 2000.
[8] W. Becker, "The turbomolecular pump, its design, operation and theory; calculation of the pumping speed for various gases and their dependence on the forepump", 2010.
[9] Ali J. Ghandour and Mohamad Jaafar Abdallah, "Design of a Lebanese Cube Satellite", 2018.

[10] V.I. Trokhanyak, "Construction mesh in Ansys meshing models for CFD finite elements method

[11] Susan M. Motil, "Capabilities, design, construction and comissioning of new vibration, acoustic and electromagnetic capabilities added to the world’s largest thermal vacuum chamber at Nasa space power facility", 2013.