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COSMICA

Executive summary

As we plan for stable lunar missions, one of the most significant obstacles is the reliance on Earth for essential resources and supplies. Given the high costs and logistical constraints of launchings and frequent resupply missions, there is an urgent need for autonomous life support systems able to minimise resource consumption and maximise efficiency. Furthermore, the unique conditions of the lunar environment, including reduced gravity, require a more in-depth study, with the final aim of cultivating innovative species providing essential resources, such as food and oxygen. In this context, the development of closed-loop systems becomes crucial. Closed-loop systems minimise waste and maximise resource recycling, creating a self-sustaining environment that reduces the dependency on external supplies. Photobioreactors for microalgae cultivation, present a promising solution as closed loop systems, due to their ability to produce oxygen, remove carbon dioxide, and provide nutritional biomass. This project aims to address these challenges by both designing and developing a photobioreactor that optimises resource use and adapts to the unique conditions of the Moon. This project proposes a modular and scalable system that can be customised and fit to standard habitat geometries and Environmental Control and Life Support Systems (ECLSS).

Major findings

Biological feasibility

Imagine these tiny photobioreactors thriving in the harsh, low-gravity landscape of the Moon, where they would need to efficiently harness this a reality, we delved into how microalgae can be optimised to grow in a controlled environment with minimal water and nutrients, all while withstanding cosmic radiation. NASA's extensive research and technical documentation substantiate the biological feasibility of cultivating microalgae in space environments.

Fluid dynamics

A key aspect in the development of a photobioreactor is the movement of microalgae and the recirculation of the culture medium. We have analysed these factors using a multiphase computational fluid dynamics simulation, ensuring that under the unique conditions of reduced gravity, these capabilities function correctly. Furthermore, we studied potential shape optimizations to enhance the performances of the photobioreactor.

Radiation shielding

An additional analysis evaluated the potential radiative shielding of photobioreactors, structures made of polyethylene and water, materials known for their shielding properties. The simulation, conducted with NASA's OLTARIS software, showed that a panel of photobioreactors can reduce the equivalent radiation dose by 34%. While a simple shield of water and polyethylene may not be sufficient on its own for long-term astronaut survival, it offers a promising complement to existing shields that could significantly enhance the safety and well-being of space explorers.

Light requirements for human beings

The lighting analysis examined the efficiency and effectiveness of the LED lighting system of the photobioreactors, exploring how it can improve the psycho-physical well-being of the astronauts. By integrating international lighting standards, the design ensures an environment that not only supports the biological growth of microalgae, but also the maintenance of circadian rhythms crucial to human health. The results underline that optimised lighting is not only a technical issue, but an essential element for the comfort and health of the space crew.

Development of a demonstrator

Eventually, we developed a demonstrator to confirm that our analyses were accurate. This prototype allowed us to demonstrate and validate the effectiveness of the modular design approach. Through the demonstrator, we were able to verify system functionality, refine component integration, and gather valuable insights into human interaction and maintenance. The demonstrator provided concrete evidence that our concepts were sound, reinforcing their viability for eventual full-scale implementation on lunar missions.

Conclusions and constraints of the solution

In our project, by integrating microalgae, we developed a modular system that contributes to creating a closed-loop system to produce O_2, CO_2 capture, and the provision of superfood. Additionally, the culture medium, mainly composed of water, adds the benefit of radiation shielding in the application area. All these features are achieved with relatively low weight and a modular design, always in parallel with scalability and adaptability to different surfaces principles. However, our design and optimization are based on the presence of gravity, albeit significantly reduced compared to Earth's gravity. As a result, this design is not suitable for microgravity conditions (e.g., the International Space Station) but is intended for use on planetary surfaces.

Recommendations

Designing a closed-loop system for space missions is complex, but a modular approach offers flexibility, scalability, and easier upgrades. By developing individual photobioreactor components separately, it reduces system-wide failures and simplifies integration. Prioritizing human factors in the design, such as easy maintenance and user-friendly interfaces, is crucial for astronauts' efficiency in lunar environments. Future developments include testing in reduced gravity to optimize microalgae cultivation and improving food quality. This technology also has potential applications on Earth, especially in extreme environments, promoting sustainable agriculture.

Key Words

Microalgae, Demonstrator, Photobioreactor, Fluid-dynamic, Modularity

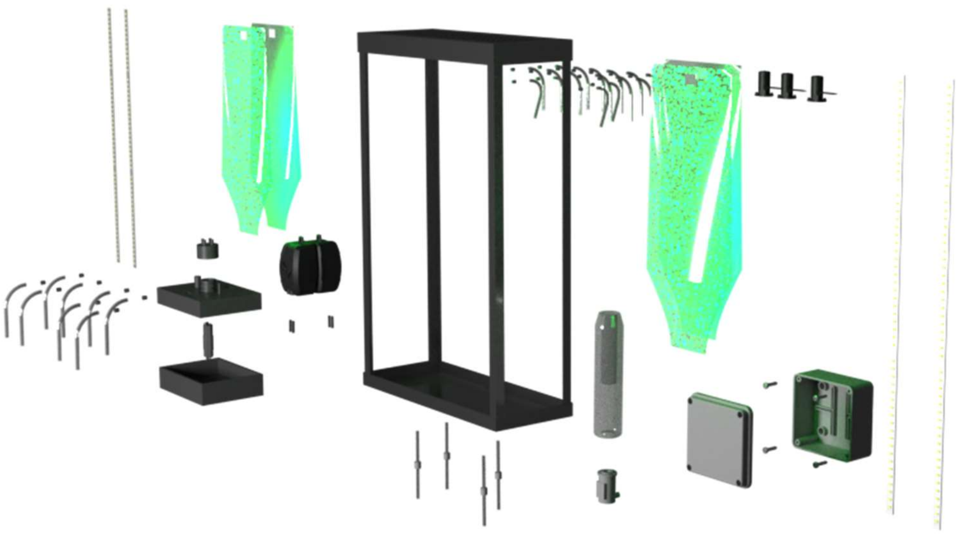
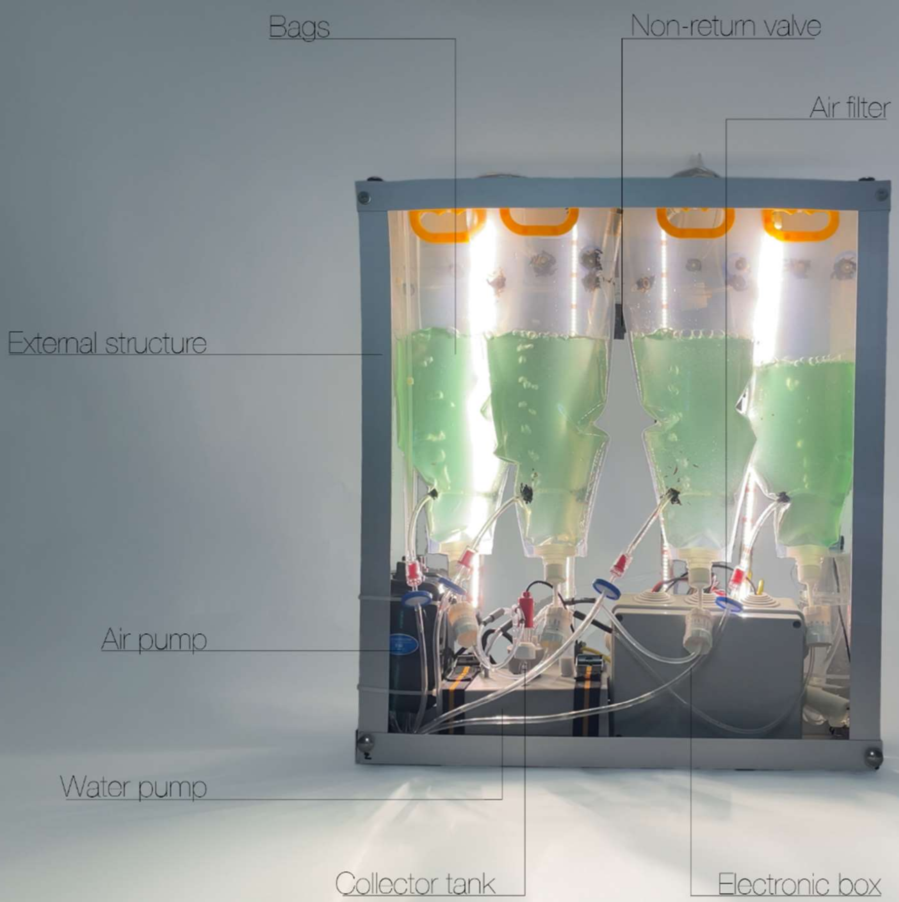
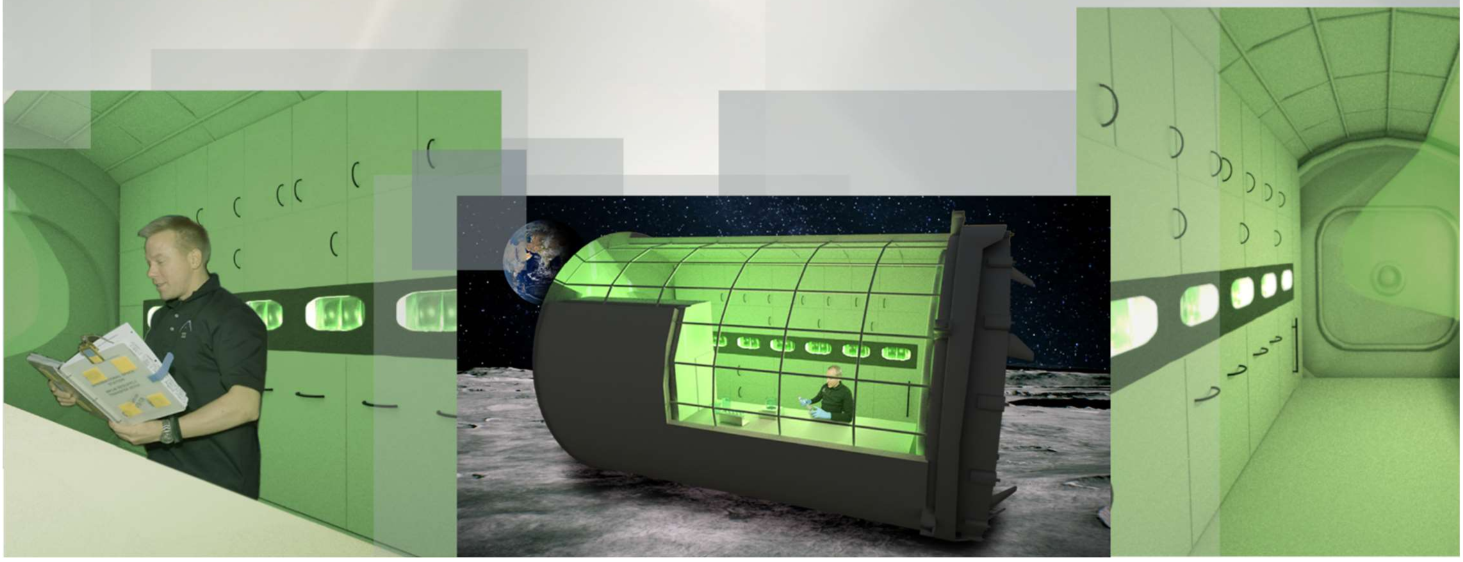


Figure 1: Exploded view of the final prototype.

COSMICA



COSMICA is a modular component with the aim of **producing microalgae** on hostile environment, specifically for **space exploration** on the moon. Its structure incorporates **multiple photobioreactors** and includes both **hydraulic and electronic systems**.



Project description written by the Principal Academic Tutor

The COSMICA project is developed within the framework of space architecture, embracing a sustainable, circular design approach for future habitats on the Moon or Mars. Unlike traditional habitats that depend on costly resources brought from Earth, COSMICA aims to create self-sustaining ecosystems using locally adaptable solutions, particularly through the innovative use of microalgae. These versatile microorganisms are central to the project's vision, providing essential resources such as food, oxygen, hydrogen, and bioproducts, which are crucial for both survival and the overall functionality of the habitat.

COSMICA's approach merges advanced computational design, multi-objective optimization, and interdisciplinary expertise spanning space architecture, biology, and engineering. A key innovation of the project is the development of modular photobioreactors designed to enhance the adaptability and scalability of the habitat. The reactors are lightweight, easily replaceable, and configurable. They can be integrated seamlessly into the overall design of the space habitat to form a water-based radiation shielding system, essential for protecting astronauts under space conditions.

To maximize the efficiency of the habitat, light distribution within the photobioreactors has been optimized to support the growth of microalgae and align with the circadian rhythms of astronauts. Our system employs tailored light spectrums that promote both plant productivity and human well-being, enhancing the overall living conditions within the habitat.

Beyond extraterrestrial applications, COSMICA offers valuable insights into sustainable design practices on Earth, aligning closely with global sustainability goals. It suggests innovative ways to reduce resource dependency, promote local production, and rethink our approach to construction and living environments. In doing so, COSMICA not only paves the way for sustainable space exploration but also offers a transformative perspective on addressing pressing ecological challenges on our planet. By integrating technology, biology, and architecture, COSMICA redefines our approach to habitat design, pushing the boundaries of sustainable living both in space and on Earth.

Team description by skill

The COSMICA team's success was driven by a harmonious blend of specialized skills and collaborative spirit. **Luigi Renzulli**, the team leader, expertly balanced his aerospace engineering background with effective communication and budget management, steering the project with both technical insight and organizational prowess. **Enrico Masiero** brought his graphic design and graphical skills to the forefront, crafting impactful visuals and presentations that enhanced the project's overall appeal and coherence.

Samuele Ferrero contributed deep technical expertise in fluid dynamics and simulation, which was vital for addressing the project's engineering challenges. Meanwhile, **Paolo Garelli**'s work in electronics and biological analysis was key in developing and refining prototypes, as well as understanding their biological performance.

Alberto Rosso applied his knowledge of complex systems physics to ensure the project met safety standards through rigorous radiation analysis, and his strong communication skills facilitated effective engagement with academic audiences. Alberto and Paolo were responsible for the financial resources of the groups and their management. Last, but not least, **Beatrice Lanteri**'s talent in user-centred design and her proficiency in graphic visualization and 3D modelling translated complex ideas into engaging, user-friendly formats.

This diverse and synergistic approach enabled the team to address challenges from multiple perspectives, fostering creativity and leading to well-rounded, innovative solutions.

Goal

COSMICA is a complex project characterized by multidimensional challenges that demand a collaborative, interdisciplinary solution. The objectives aim to address many of the unanswered questions posed by space exploration missions. The project's primary focus lies in designing an innovative and sustainable technology capable of supporting the creation of a closed-loop system through the integration of microalgae culture. In parallel, the Team undertook the theoretical description of the technology, conducting comprehensive analyses to fully characterize the developed components and ensure their seamless integration into extreme space habitats. The project emphasized the fusion of technical and human factors, prioritizing both aspects. Finally, the Team developed a fully functional demonstrator to test and verify the functionalities of the proposed design. This early prototype was designed to be suitable for both space and terrestrial use.

Understanding the problem

As we plan for stable lunar missions, one of the most significant obstacles is the reliance on Earth for essential resources and supplies. Given the high costs and logistical constraints of launchings and frequent resupply missions, there is an urgent need for autonomous life support systems able to minimise resource consumption and maximise efficiency. Furthermore, the unique conditions of the lunar environment, including reduced gravity, require a more in-depth study, with the final aim of cultivating innovative species providing essential resources, such as food and oxygen. In this context, the development of closed-loop systems becomes crucial. Closed-loop systems minimise waste and maximise resource recycling, creating a self-sustaining environment that reduces the dependency on external supplies. Photobioreactors for microalgae cultivation, present a promising solution as closed loop systems, due to their ability to produce oxygen,remove carbon dioxide, and provide nutritional biomass. This project aims to address these challenges by both designing and developing a photobioreactor that optimises resource use and adapts to the unique conditions of the Moon.

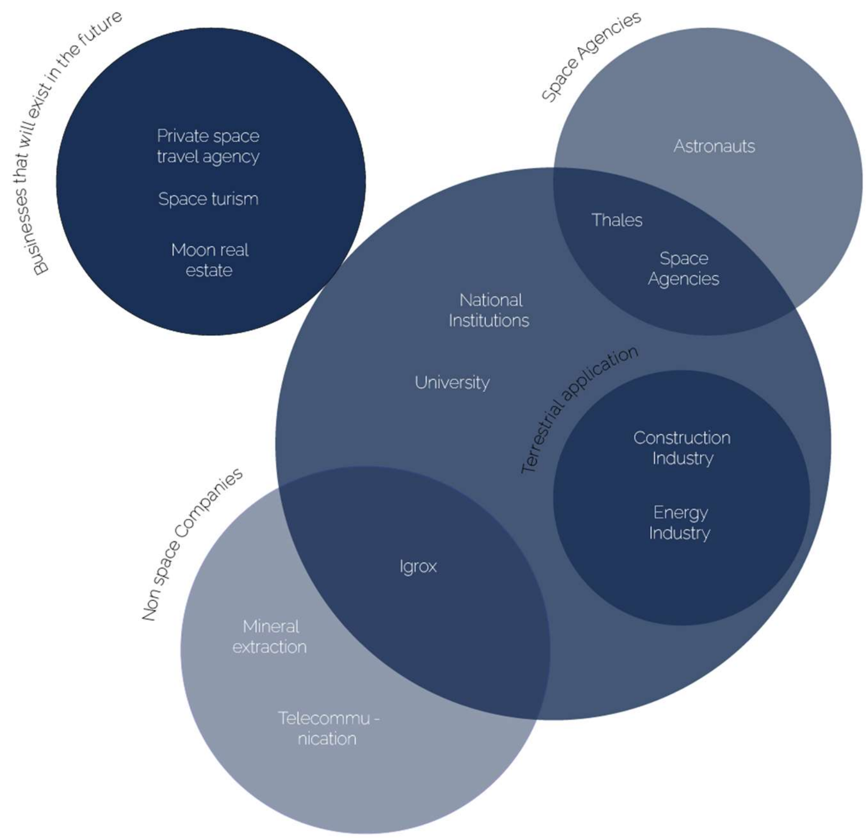


Figure 2: Stakeholders map.

Microalgae are eukaryotic, photosynthetic microorganisms that thrive in aquatic environments and can survive extreme conditions, making them valuable in fields like space exploration and sustainability [1]. They are key players in the green transition due to their ability to convert CO2 into biomass through oxygenic photosynthesis.

Microalgae have a wide range of applications, including nutraceuticals, superfoods, biofertilizers, and bioremediation for wastewater and soil. One of the most notable species, **Spirulina** (*Arthrospira platensis*), is a cyanobacterium known for its high nutritional value, containing proteins, vitamins, and minerals. Its simple cultivation requirements and rich nutrient profile have made it a popular superfood globally.

Photobioreactors are closed systems used to cultivate microalgae in controlled environments, offering higher efficiency and less contamination compared to open ponds. While more land-efficient, they come with challenges such as high costs and complex designs. Tubular photobioreactors, using transparent tubes and air spargers for CO2 distribution, require careful management to prevent algae aggregation [2].

Microalgae are gaining attention in space exploration, notably in the **MELiSSA project** by the European Space Agency, which aims to create a closed-loop life support system for recycling food, water, and oxygen in space [3]. The **COSMICA project** contributes to advancing these technologies for sustainable space missions.

Figure 3: Photobioreactors cultivation system.

Exploring the opportunities

The evolution of the design is characterized by a progression towards more modular and efficient solutions for integrating photobioreactors into space habitats. As we learned during the second ASP school, design is usually a cybernetic process, where selecting a final concept or idea is not easy since designing is more similar to a loop process rather than a linear one.

The initial proposal, which envisioned an entire space module dedicated to the integration of photobioreactors, represented an ambitious but complex approach, requiring significant space and structural modifications. The idea behind the first concept of the solution that we imagined, was to think and develop a solution for an entire space module, dedicated completely to the microalgae cultivation, serving and identified himself as a closed loop system. The next evolution of the concept refined this first idea by embedding the photobioreactors within the walls of the space module, thus optimizing the use of space and enhancing the overall efficiency of the habitat design. The focus shifted to a more technical challenge, but within a specific sector and area of the module, rather than taking into account the all module as a whole. However, this was not the optimal solution for us, mainly due to the fact that the maintenance operation and the total structure was still too big to optimize and take every aspect into consideration. The third and final proposal epitomizes the need for a more adaptable and straightforward solution and also a solution more focused on the essential element of the closed loop system, the photobioreactor.

It introduces a modular component for the cultivation of microalgae that can seamlessly integrate into various surfaces within the habitat. This design not only simplified the installation and maintenance processes but also offers greater flexibility in terms of application, making it an ideal solution for the dynamic and constrained environment of space habitats. This evolution underscored the importance of modularity and simplicity in the design of life support systems for space exploration, ensuring that they can be easily adapted to different mission requirements and environmental conditions

Generating a solution

Starting from the scenario and demand system analysis, after defining the needs and requirements of the main stakeholders, the COSMICA concept was born, capable of responding optimally to the challenges posed by design in space. Nowadays, in fact, innovation aims to integrate technology with economic needs and scarce resources, without neglecting the human and environmental factors. It is no coincidence that we speak of economic, social and environmental sustainability; therefore, good design must necessarily take these three factors into account and ensure the best integration between them. In order to best guarantee this innovative concept of sustainability also in the space sector, COSMICA aims to produce components that can be used in long-term missions and that optimize maintenance times, which must be minimal, simple and immediate with a view to preventing errors. From this point of view, the components must guarantee maximum effectiveness and reliability.

Designing in an isolated, inhospitable and extreme environment such as space presents a real challenge. To respond optimally to this challenge, it is necessary to adopt innovative approaches using a circular design methodology. The objective of the COSMICA project, in fact, is to participate in the realization of a 'full closed loop system' that integrates technology with the use of microalgae, especially spirulina. This type of algae is in fact particularly versatile and can find applications in various sectors, connecting different design fields that influence each other. Indeed, the integration of microalgae in space can contribute substantially to the creation of a self-sufficient and cyclic control system in which microalgae are used to produce essential resources, like oxygen and nutrients, within a confined environment such as a lunar module. This continuous process maintains an ecological balance, reducing the need for external resources and improving the self-sufficiency of the space environment. The system constantly monitors and regulates internal conditions, such as light, temperature and radiation levels, to optimize microalgae growth and ensure the stability of the microalgae life cycle, while contributing to the astronaut's physical and psychological well-being. As mentioned before, the COSMICA project answers to the needs of various stakeholders with the objective of improving astronauts' life during space exploration missions. It is thus compulsory to comply with the general contingencies of a typical mission, which presents several issues. Among them, the space factor is certainly one of the most challenging. Being the weight of launched materials limited, a hypothetical lunar outpost cannot exceed prefixed dimensions and thus offers small operational spaces for astronaut movement and thus to technological equipment, too. Moreover, prototypical lunar modules adopt several different geometries and shapes that almost never recall the terrestrial orthogonal symmetries. Given these constraints, COSMICA aims at the realization of a prototype whose main characteristic is to be highly adaptable to different geometries. By taking inspiration from worldwide spread architectures, one immediate solution to the necessity of adaptability is modularity. By modularity one means the property of a system of being decomposed in smaller separate independent units. This feature also facilitates the unit's maintenance and direct accessibility by astronauts. Therefore, single elements will be independent but together will also create a valuable support system that will smoothly integrate with any geometry imposed by the space architecture chosen. In order to guarantee maximum reliability and efficiency, necessary in an extreme environment such as space, each element has been studied and designed to optimize the design of the solution. Each individual unit, in fact, consists of a specific number of photobioreactors communicating with each other, whose spatial arrangement facilitates the insertion of electronic and mechanical components to regulate the flow of water and mineral salts. The latter are essential for the growth and survival of the microalgae and are precisely weighted by the implemented automation system.

With a view to circular design, the water in the system is not wasted, but constantly re-enters the system after each withdrawal of microalgae, which are separately dried and prepared for food use. Another essential element for microalgae culture are the

LED lights, which uniformly illuminate the culture medium, allowing the microalgae to grow properly and improving the ‘human factor’. The green light produced can in fact have positive developments on the psychological factor as it is linked to the concept of nature and calmness.

Furthermore, this light increases productivity and can have benefits on the physical level and on the immune system [4]. Finally, the designed components possessing a high degree of adaptability can be positioned along the surfaces of the space module and thus provide additional shielding from the cosmic radiation and lunar albedo to which the environment is exposed.

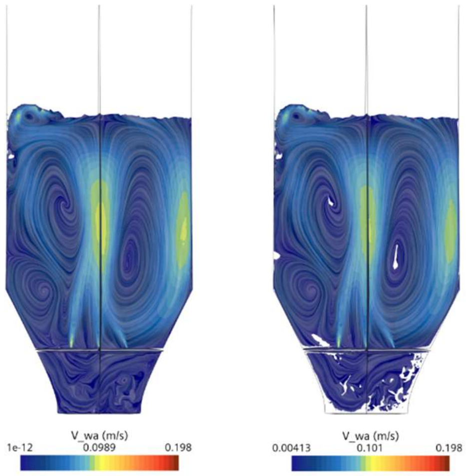


Figure 4 : Final results STAR-CCM+ Fluid-dynamic analysis in Moon conditions [5].

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