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DESIGN & SIMULATION OF A PHOTOBIOREACTOR TARGETING CARBON CAPTURE IN A PRESSURIZED SYSTEM

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Abstract

Carbon capture systems have been an area of interest since they have the potential to greatly reduce the carbon footprint. Biological carbon capture & utilization systems have the potential to provide better solutions in terms of cost & environmental constraints. In this work, a low-cost pressurized photobioreactor model has been designed and the safety of the pressurized system has been evaluated. Pressurized system is preferable to elevate the carbon capture efficiency. In order to design such a system that can be effective to run in a laboratory setting, several factors have been considered. The results suggest yield strength of the material (60 MPa) is greater than the maximum stress (48.63 MPa) of the system. The photobioreactor houses a composition analyzer at the top & a sparger at the bottom. Stress analysis of the photobioreactor reports a factor of safety of 4.2 and a deformation scale of 1. A hydrodynamic study has been carried out on SolidWorks 2022 to verify the safety of the photobioreactor model in the operation phase. The pressure inside the photobioreactor was found in between 2.69 atm to 2.7 atm for 2 m/s of air velocity at the inlet of the photobioreactor model. The vorticity found was in between 0 to 25.71. Efficient design of large scale industrial photobioreactors may reduce the cost of carbon capture & valorize the process.

Keywords: Carbon capture, Photobioreactor (PBR) model, Closed loop, Stress Analysis, Safety

1. Introduction:

Global energy demand is increasing rapidly, leading to excessive fossil fuel consumption, which has a significant carbon footprint and poses serious environmental risks. It is significantly uprising to emissions of GHG, resulting in global warming. Alternatives of conventional energy sources are required for a sustainable future. Carbon capture and utilization (CCU) technology aimed at reducing atmospheric CO_2 levels has been researched and widely implemented around the globe. [1] Biomass is increasingly favored worldwide for power generation because of its sustainability, potential, and environmental advantages. Additionally, biomass is nearly carbon neutral and can greatly lower net carbon and hazardous emissions. [2] As a result, the world needs energy sources of renewable and sustainable in nature there is an urgent need for renewable and sustainable energy sources.

Biomass offers a more sustainable long-term solution as a renewable energy source derived from trees, plant residues, energy crops, algae, animal waste, and other materials. Biofuel is the dominant form of biomass energy, as it absorbs CO_2 and generates lower emissions. [3] However, conventional biofuels raise concerns about food insecurity due to their reliance on food crops for biomass production.[4] Second-generation biofuels, produced from agricultural byproduct and various plants, have higher energy content but require significant land resources, prompting interest in alternative sources. Third-generation biofuels from microalgae and

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cyanobacteria could alleviate current biofuel demand. [5] Additionally, fourth-generation biofuels, derived from metabolic modification of microalgae, enhance product separation. [6] Compared to third-generation biofuels, Fourth-generation biofuels absorb more CO_2 and provide greater yields of microalgae, along with enhanced lipid content and production rates. Microalgae are photosynthetic microorganisms capable of producing biomass when exposed to light and carbon dioxide. [7] This diverse, polyphyletic group includes micro and macro algae. Traditional microalgae production in open pond systems faces several limitations, including low biomass productivity, restricted algae strains, contamination, and requirements of larger land area. These challenges can be addressed using photobioreactors (PBRs), which are containers designed for cultivating microalgae. PBRs can be open, closed, or semi-closed and are made from transparent and waterproof materials. [8] To achieve maximum growth rates for algae, a combination of light, CO_2, water, and various nutrients is essential. Aeration using flue gas serves as a significant source of CO_2 exchange between the culture water and input air, helping to circulate the culture, prevent cell settling, and ensure uniform conditions like light exposure and water quality. Flue gas can be absorbed and converted into biomass, potentially for biofuel production. Effective mixing is crucial for maintaining uniform temperature, preventing cell settling, supplying CO_2 to the medium, and removing oxygen by the rate at which mass is transferred. [9] Large bubbles circulate water more effectively and improve mixing compared to small bubbles, which are generated by fine pore diffusers and offer a larger surface area for gas exchange, resulting in better mass transfer. [10] An improved mass transfer rate enhances CO_2 absorption by algae; as CO_2 is consumed by the culture, the pH rises. Most microalgae variety thrive at a pH range of 7-9, with optimal levels between 8.2 and 8.7. [11] An automated CO_2 injection system with a uniform distributor helps maintain stability in both CO_2 levels and pH. Additionally, light significantly influences the efficiency of a photobioreactor (PBR) system, as light intensity affects microalgae growth rates. [12] While various studies have explored PBRs and carbon sequestration separately, few have systematically investigated the synergistic effects of pressurization on biomass productivity and CO_2 uptake under real-world conditions. [13] Existing models lack high pressure closed loop PBR systems on pilot scale. Addressing these gaps could lead to more effective PBR designs that significantly enhance carbon capture capabilities.

This study aims to design a conceptual photobioreactor model with a closed loop to incorporate a pressurized system and evaluate its safety during its static and operational phase. The computer aided design is carried out to test the possibility of building a functional and safe to operate photobioreactor at pilot scale that will be able to withstand high pressure and will be sustainable at the same time.

2. Materials:

The Figure 2.1 illustrates the schematic of the conceptual photobioreactor model. The photobioreactor consists of a cylindrical chamber, gas inlet, gas sparger, gas composition analyzer at the headspace, gas flow controller, closed loop for gas utilization and optimization, valves for gas flow control and support for the cylindrical chamber. The computer aided drawing of the closed loop conceptual photobioreactor was carried out in SolidWorks 2022 software. Table 2.1 describes the design parameters undertaken and Figure 2.2 illustrates the computer aided drawing. Since high pressure may develop in such closed loop photobioreactor. Polycarbonate was selected as the construction material for the chamber as it can withstand high pressure while maintaining acceptable optical characteristics required for a PBR.

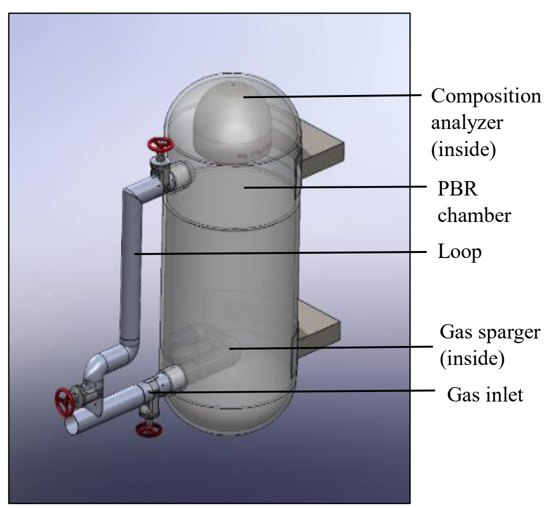

Figure 2.1: Schematic of the conceptual photobioreactor model

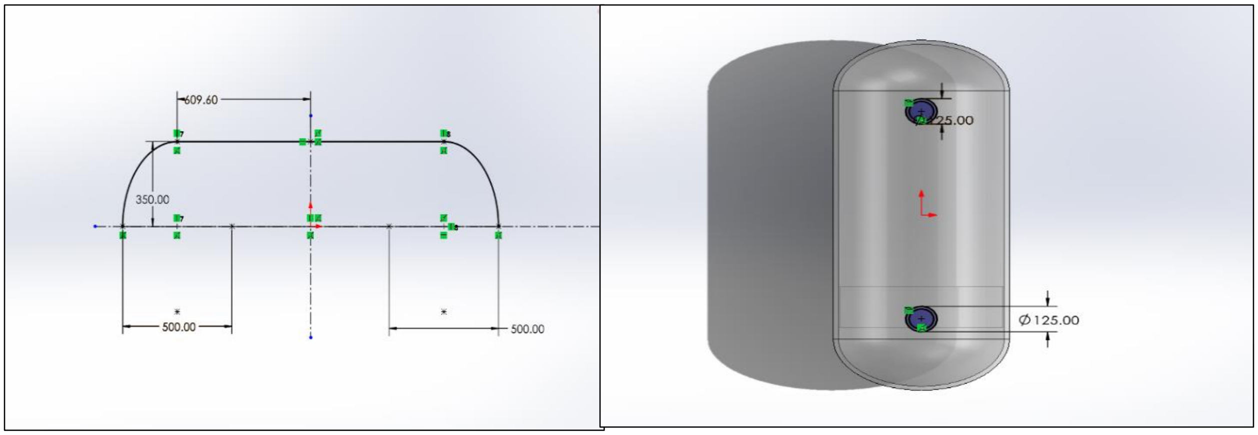

Figure 2.2: The Drawing of the Conceptual Photobioreactor Model by SolidWorks 2022

3. Methodology:

The simulation study was conducted in SolidWorks 2022 to investigate the behavior of the photobioreactor under applied pressure and to evaluate its safety.

Table 2.1: Design Parameters

Parameters	Dimensions
Length of the pressure vessel	1719.22 mm
Volume of the pressure vessel	80 L
Surface area of the pressure vessel	7.94 m^2
Diameter	350 mm
Thickness	20 mm
Diameter of the upper and lower openings	100 mm
Sparger hole diameter	5 mm
Length of pipe	1180 mm
Pipe diameter	100 mm
Yield strength of Polycarbonate	60 MPa

Different hydrodynamic characteristics inside the photobioreactor under dynamic conditions were also evaluated. The inlet velocity of the gas was taken 2m/s. Air was considered as model gas and freshwater was considered as a model culture medium of microorganisms for the model photobioreactor. Temperature of 20 degree Celsius, the highest pressure allowed inside the reactor was 3 atm & environmental pressure of 1 atm. Water was filled to 2/3rd of the total length of the PBR.

4. **Result and Discussion:**

Static behavior of the PBR was evaluated in the simulation study. Static stress and strain test is carried out usually to evaluate the strength of the structure, residual stress, deformation behavior and many more. [14] The yield strength of the polycarbonate made cylindrical PBR chamber was 48 MPa. Figure 3.1 depicts the plot of static nodal stress of the PBR where the highest stress was found out below 14 MPa.

According to the Figure 3.2, the highest strain observed was 0.002. The maximum displacement under applied pressure was found to be 1.2 mm as shown in Figure 3.3. These results imply that the stress occurred under pressure is below 48 MPa and this is why the PBR will be safe to operate. Displacement of 1.2 mm was found at the mid-section of the PBR which is negligeable. [15]

Factor of safety (FOS) is defined as the ratio of material strength and applied stress. [16] A FOS >1 means the material strength is higher so that the applied stress will not cause failure. [17] This simulation study reveals the FOS of the PBR to be 4.2 which indicates the PBR will be safe to operate at the pressure considered. Moreover, the FOS is not too high which also indicates the chamber is not unnecessarily overdesigned, implies a preferred design outcome for the PBR. [18] This help the designed PBR achieving a balance among material optimization, safety and cost. [19]

The hydrodynamic studies of the PBR presented in Figure 4.1, 4.2, 4.3, 4.4, 4.5 reflect the overall pressure, overall density of the fluid, velocity distribution, vorticity generation and combined effect

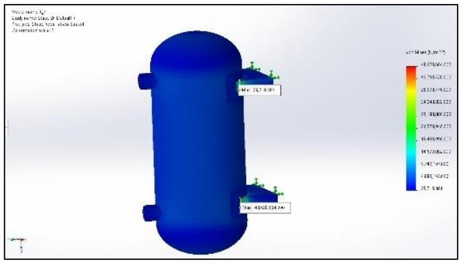

Figure 3.1: Static Stress

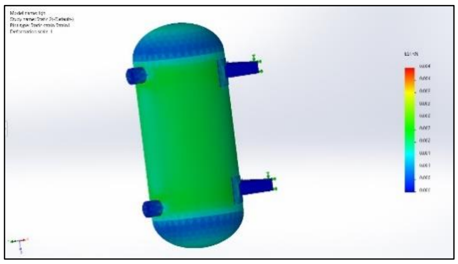

Figure 3.2: Static Strain

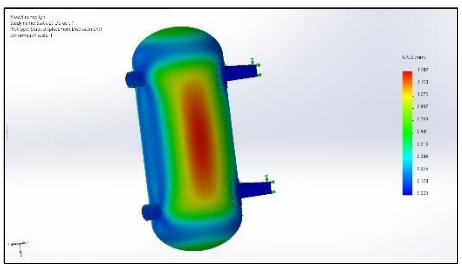

Figure 3.3: Static Displacement when pressure applied

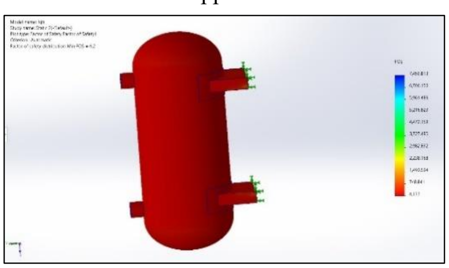

Figure 3.4: Factor of Safety

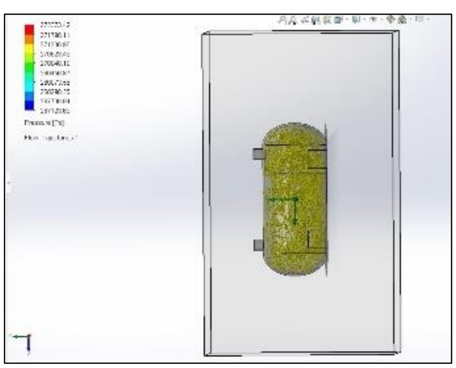

Figure 4.1: Overall Pressure

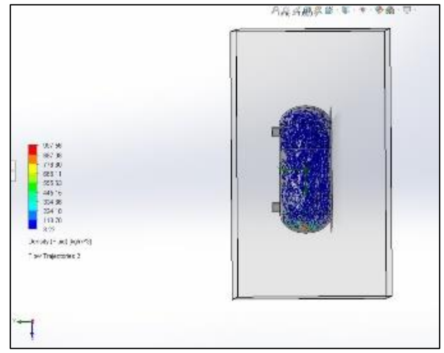

Figure 4.2: Overall Density of the fluid

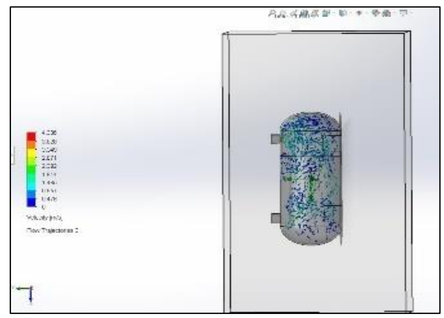

Figure 4.3: Velocity Distribution

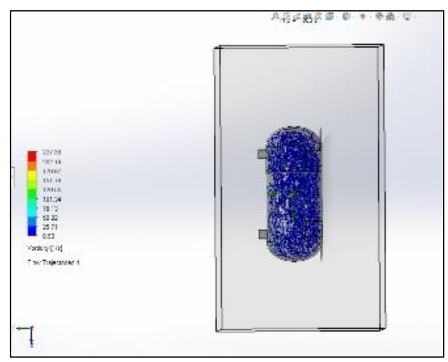

Figure 4.4: Vorticity Generation

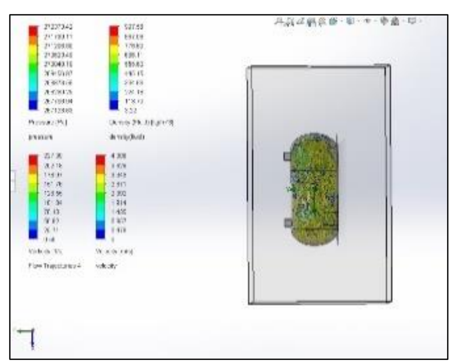

Figure 4.5: Combined effect of pressure, density, vorticity and velocity

of pressure, density, vorticity and velocity respectively.

From Figure 4.1, it can be observed that the overall pressure is fairly distributed inside the PBR chamber. The highest value for pressure inside the PBR did not exceed 0.28 MPa while the maximum yield strength of the polycarbonate construction material of the PBR is 60 MPa. This indicates the internal pressure is quite negligeable which is favorable for algal growth as the algae will not be subjected to high shear stress which may significantly limit its growth.

The highest density of the fluid in the PBR was 998 kg/m^3 at the sparger area at the bottom of the PBR as shown in Figure 4.2. Since the system comprises air, most of the flow trajectories show the density of air bubbles. The uniform distribution of flow trajectories depicts the air is mixed and contacted with water all over inside the PBR, further indicating good gas liquid contact and mass transfer.

Velocity of the gas inside a PBR impacts the efficiency by proper gas liquid contact, mixing, agitating the mixing for good diffusion of oxygen bubbles to be transferred to microorganisms. The inlet gas velocity of 2-8 m/s is good for homogenous bubble distribution.[20] On this study, the inlet gas velocity was kept constant at 2m/s which lost its velocity after getting into the PBR chamber through the sparger, ranging from 0.01-1.4 m/s of velocity. The trajectories observed from the Figure 4.3 indicate the air flows in a zigzag manner in the PBR. In most cases the gas velocity was below 0.5 m/s inside the PBR which means the reactor will be stable at this gas inlet velocity and the air velocity will not destabilize the operation in the PBR.

Vorticity impacts the PBR in effectiveness of mixing of the gas and liquid in the PBR. Acceptable vorticity generation prevents building up of dead zones in the reactor which in turn prevents non-homogeneous oxygen distribution thus non-uniform biomass and subsequent biofilm growth.[21] In our case, the vorticity was 17.7/s according to Figure 4.4. This indicate the swirling in the PBR is effective for algal growth. [22]

Figure 4.5 illustrates the combined effect of the parameters discussed above on the PBR. The loop and the valves make the pressurized system work in a synergy of all the considered parameters.

4. Conclusion:

The results show that this kind of photobioreactor will be safe to operate at different conditions. Also, the other parameters are within acceptable limits.

This study has been conducted on a simple photobioreactor model that may be constructed & used under solar irradiation. This study has been done taking water as the primary fluid in the reactor. In future study, more realistic scenarios can be taken into account to model such photobioreactors such as taking real algal solution into account as well as counting their density, viscosity and other biological phenomena to better predict the characteristics of a real low-cost pilot scale photobioreactor. In this study, the surface area to volume ratio was 99.28/m, a low ratio which limits its photo absorption efficiency to work as an efficient PBR. The PBR can also be simulated in the real solution at varying sunlight conditions, temperature, pH, oxygen and carbon dioxide flow rates and their gas liquid mass transfer rates. Proper utilization of flue gas through this system is challenging as the gas must be controlled continuously without hampering the growth of microorganisms. In the future, implementing control system & dynamic controls on the overall system based on the real time data from the composition analyzer, can be a effective way to utilize the flue gas replacing air through the gas inlet and controlling the nitrogen content in the headspace. Outcome of this study may lead to choosing better materials such as composite or hybrid materials which may be used for other geometries to achieve both the goals of pressurized system and high surface area to volume ratio at the same time in the photobioreactor.

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