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Design and Finite Element Simulation of Hydrothermal Carbonization Reactor

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Abstract
This study presents the design and simulation of a Hydrothermal Carbonization (HTC) bioreactor using finite element analysis (FEA) to evaluate its structural integrity under high-temperature and high-pressure operating conditions. The bioreactor, constructed from Stainless Steel 304 with a 5 mm wall thickness and designed to operate at 10 MPa and 300 °C, was analyzed for pressure distribution, thermal stress, Von Mises stress, safety factor, fatigue life, buckling resistance, and combined thermo-mechanical loading. Results showed that the reactor maintains structural stability with stress levels below the material yield limit and acceptable safety factors. Localized fatigue concerns were observed around geometrical discontinuities, emphasizing the need for targeted reinforcement. The combined fatigue–thermal–structural life analysis confirms the reactor's suitability for prolonged cyclic operation. Overall, the bioreactor design is robust and efficient, supporting its application in sustainable biomass conversion processes.

Keywords: Bioreactor, Hydrothermal Carbonization, Finite Element Analysis

1. Introduction

Energy is a vital necessity for human society and plays a critical role in driving global economic progress. Presently, the world heavily relies on fossil fuels as its primary energy source, but this is depleting at an accelerated pace (Jie et al., 2023). The widespread utilization of this fuel to meet the energy demands in industrial, residential, and transportation sectors has also resulted in significant level of greenhouse gas emissions. These emissions have contributed to environmental pollution, global warming, and climate change (Hassan et al., 2024). However, alternatives to the use of fossil fuels is being explored. One of such alternatives is the biomass. At present, biomass contributes to approximately 10 % of the total global energy consumption on an annual basis (Saleem, 2022). Sikkema et al. (2021), report that it is considered as the fourth largest energy resource. However, the utilization of raw biomass is restricted due to its

low energy properties and the production of smoke resulting from its high moisture content (MC), volatile matter (VM) content attributes and high hydrophilic nature (Jie et al., 2023).
Energy in biomass can be released through different biological and thermochemical processes by breaking the chemical bonds between adjacent oxygen, carbon, and hydrogen molecules (Begum et al., 2024). In addition to the traditional method of producing carbonised fuel from biomass, the hydrothermal carbonization (HTC) process offers distinct benefits (MacDermid-Watts, 2021; Zhang et al., 2023).
Hydrothermal carbonization (HTC) is a highly favoured thermal conversion method due to its ability to effectively process feedstock with high moisture content of 70 – 90 % by weight without prior drying (Zhang et al., 2023; Singh et al., 2024). HTC has the potential to transform lingnocellulose into substances resembling coal, imitating the natural process known as hydrochar formation (Güleç et al., 2020; Satari and Kianmehr, 2025). However, the HTC technique is underexplored in Africa despite the huge high moisture content agricultural residues in abundance. In addition, despite the potentials of the HTC, its practical adoption for agricultural waste valorization is hindered by several critical technical gaps, especially in the design and simulation of efficient HTC bioreactors (Ojewumi and Chen, 2024).
Furthermore, there is also limited integration of computational design tools in HTC bioreactor development, especially for the conversion of high moisture content agricultural residues (Ubene et al., 2022). Advanced modeling of heat transfer, fluid flow, structural integrity, and pressure dynamics using tools like SolidWorks, ANSYS, or COMSOL is rarely applied to optimize reactor geometry and performance under realistic operating conditions (Alsharea et al., 2025).
Although, modelling and simulation of models have some limitations but it has become a useful tool for cost reduction, helps to reduce time wasting and improves accuracy in design process. Therefore, this study aimed to design and simulated a mini HTC reactor that will be suitable and efficient for the conversion of high moisture content biomass to solid biofuel.

2. Materials and Method

2.1 Materials

The 3D model of the bioreactor was developed using SOLIDWORKS 2024, which provided parametric modeling, assembly simulation, and integration with analysis tools. Typical agricultural residues were used as model biomass to determine the working capacity and design dimensions. The materials selected are given in Table 1.

Table1: Components of the Bioreactor

Component	Material	Justification
Reactor vessel	Stainless Steel 316L	High corrosion resistance and strength
Insulation layer	Ceramic Fiber Wool	High thermal resistance
Heating element ring	Nichrome wire	Uniform heating, stable at high temperature
Gasket/Seals	PTFE (Teflon)	Chemically inert and temperature resistant

2.2 Design consideration

Designing a Hydrothermal Carbonization (HTC) Bioreactor involves several design considerations to ensure safety, efficiency, and scalability. The key design considerations are shown in Table 2.

Table 2: Design Considerations

S/N	Factors	Description
1.	Pressure rating	The reactor must withstand pressures typically between 2–10 MPa, depending on the temperature and feedstock.
2	Temperature rating	HTC processes operate at 180–300°C, so materials and insulation must handle this range.
3	Material selection	Use stainless steel (e.g., 304 or 316) for corrosion resistance and high temperature/pressure capability.
4	Wall thickness	Based on ASME codes or Lamé's equation; thickness should support internal pressure with a safety factor ≥ 2.
5	ASME Pressure vessel Code	For pressure design and safety margin.
6	Safety compliance	Must meet OSHA, CE, or local regulations for pressure vessels.

2.3 Reactor Design

2.3.1 Determination of Height of Reactor

The design of the reactor is based on **volume requirement** for batch processing of agricultural biomass + water (HTC requires water in a biomass – to –Water ratio of ~1:5 to 1:10). (Ischia and Fiori, 2021). Assuming a Lab-scale testing of HTC with approximate volume of 5L.

$$V = \pi(\frac{D}{2})^2 \times H \quad (1)$$

$$H = \frac{V}{\pi(\frac{D}{2})^2} \quad (2)$$

$$H = \frac{5}{3.142(^{0.15}/_{2})^2} = 0.30m$$

2.3.2 Determination of wall Thickness

The thickness of the bioreactor is based on internal pressure using thin-wall pressure vessel theory, acceptable for thickness < 1/10 of internal diameter. For a cylindrical pressure vessel under internal pressure the thickness was determined as given in Equation 3 (Ala *et al.*, 2025).

$$t = \frac{P \times D}{2 \times \sigma_{allowwable} \times \rho} \quad (3)$$

Where;

t = required wall thickness (mm)

P = 3 MPa = 3 N/mm² (Assumed pressure)

D = 150 mm

$\sigma_{allowable}$ = 100 MPa (for SS316L at elevated temp)

E = 0.9 (weld efficiency)

Therefore $t = 2.524mm$

Although the minimum required thickness is = 2.5 mm, but 5 mm was selected for safety reasons.

2.3.3 Determination of Maximum Allowable Pressure

Determining the Maximum Allowable Working Pressure (MAWP) ensures the bioreactor can safely withstand internal pressure during operation. It validates the wall thickness, guides safety valve design, and ensures compliance with ASME standards (Messner et al., 2024), especially under high-temperature hydrothermal conditions where material strength may reduce. The maximum pressure was determined using Equation 4.

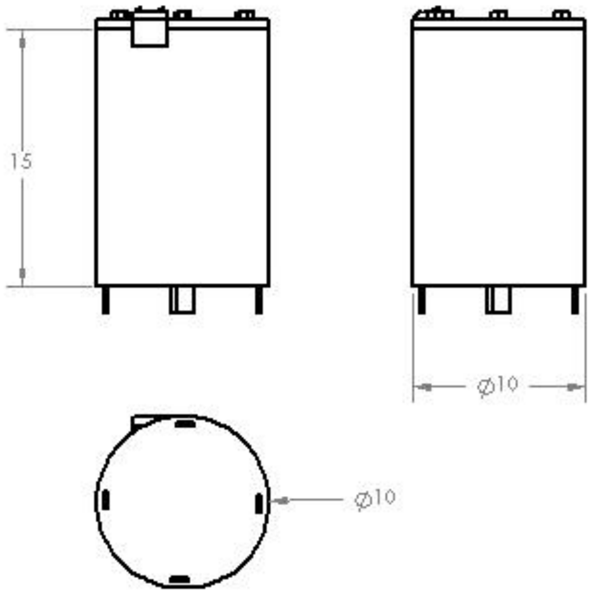
$$P = \frac{2 \times t \times \sigma_{allowable} \times E}{D + 0.6t} \quad (4)$$

$P = 5.9MPa$

This means the vessel could withstand up to 5.9 MPa.

2.4 Procedure for Bioreactor Simulation

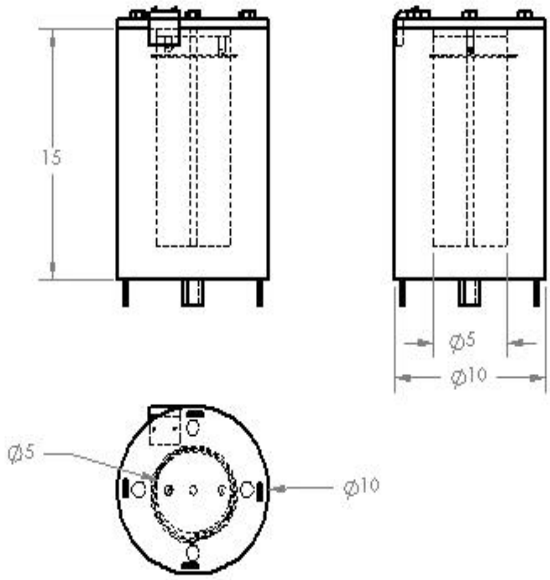
The simulation the designed HTC (Hydrothermal Carbonization) bioreactor in SOLIDWORKS, begins by modeling the complete 3D geometry of the bioreactor, ensuring it includes the main cylindrical chamber, inlet and outlet ports if necessary, and the structural stands. The bioreactor should have a wall thickness of 5 mm and be constructed from stainless steel 304. After the geometry is modeled, the SOLIDWORKS Simulation add-in is initiated and assigns the material properties to select stainless steel (AISI 304) which includes key properties such as an elastic modulus of 193 GPa and a Poisson’s ratio of 0.3. Begin with a thermal simulation by applying a fixed temperature boundary condition (e.g., 300 °C) at the ring heater (located midway along the reactor wall) and set the external surfaces to ambient conditions (e.g., 25 °C with convective heat transfer). After running the thermal analysis, create a static structural study and import the thermal results as a thermal load. Apply an internal pressure of 10 MPa and fix the base supports to simulate how the reactor is held. Evaluate the resulting Von Mises stress, displacement, and safety factor. For fatigue analysis, use the stress results under cyclic loading assumptions and apply Basquin’s law using the S-N curve for stainless steel to estimate fatigue life. A buckling analysis should also be performed by applying compressive pressure and solving for critical load factors. Finally, for more comprehensive insights, include thermal expansion stress analysis and generate detailed plots and reports covering all simulation results. Figure 1 (a) and (b) shows the autographic drawings of the bioreactor.



(a)

(b)

Figure 1a,b: Autographic Drawing of the Reactor



3. Results and Discussion

The thermal simulation result of the hydrothermal carbonization (HTC) bioreactor in Figure 2a reveals a concentrated heat distribution centered around the midsection, where a ring heating element is positioned. The temperature gradient ranges from 175 °C at the cooler top and bottom regions to 300 °C at the heated middle, indicating effective localized heating. This distribution confirms efficient thermal delivery to the biomass reaction zone but also shows the presence of significant thermal gradients that could induce expansion-related stresses, this is similar to the result reported by Li et al. (2023). The pressure simulation analysis of the HTC bioreactor (Figure 2b) indicates the distribution of internal stresses resulting from the operational pressure applied within the cylindrical vessel. The results showed that the highest stresses are concentrated around critical features such as the vessel's top cover bolts, nozzle connections, and structural discontinuities—particularly at points where the geometry changes abruptly. The cylindrical shell experiences relatively uniform pressure distribution, but localized stress intensities occur near openings and junctions, which are typical weak points under internal loading. Riyar and Bhowmik (2023) suggested the importance of reinforcing such as the critical regions to prevent failure due to yielding or fatigue.

The Von Mises stress result in Figure 2c of the HTC bioreactor indicated that the highest stress concentrations occur around geometrical discontinuities such as the bolt holes, leg supports, and the junction between the cylindrical body and end caps. These regions experience complex stress states due to bending, shear, and axial forces. However, the overall stress levels remain below the yield strength of the construction material (typically stainless steel or a similar alloy), this tally the result of analysis by Li *et al.* (2023) indicating that the bioreactor can safely withstand the applied loads without yielding. The distribution pattern of the Von Mises stress also validates the structural integrity of the design.

The fatigue analysis result of the HTC bioreactor shown in Figure 2d revealed critical regions typically around welded joints, nozzle interfaces, and support legs where stress concentration leads to reduced fatigue life. These areas experience cyclic stress fluctuations due to pressure changes, thermal expansion, and mechanical agitation, making them susceptible to crack initiation and propagation. Riyar and Bhowmik (2023) state that the fatigue life map shows that while most of the bioreactor's body has a long service life, localized zones may fail earlier if not properly reinforced or treated.

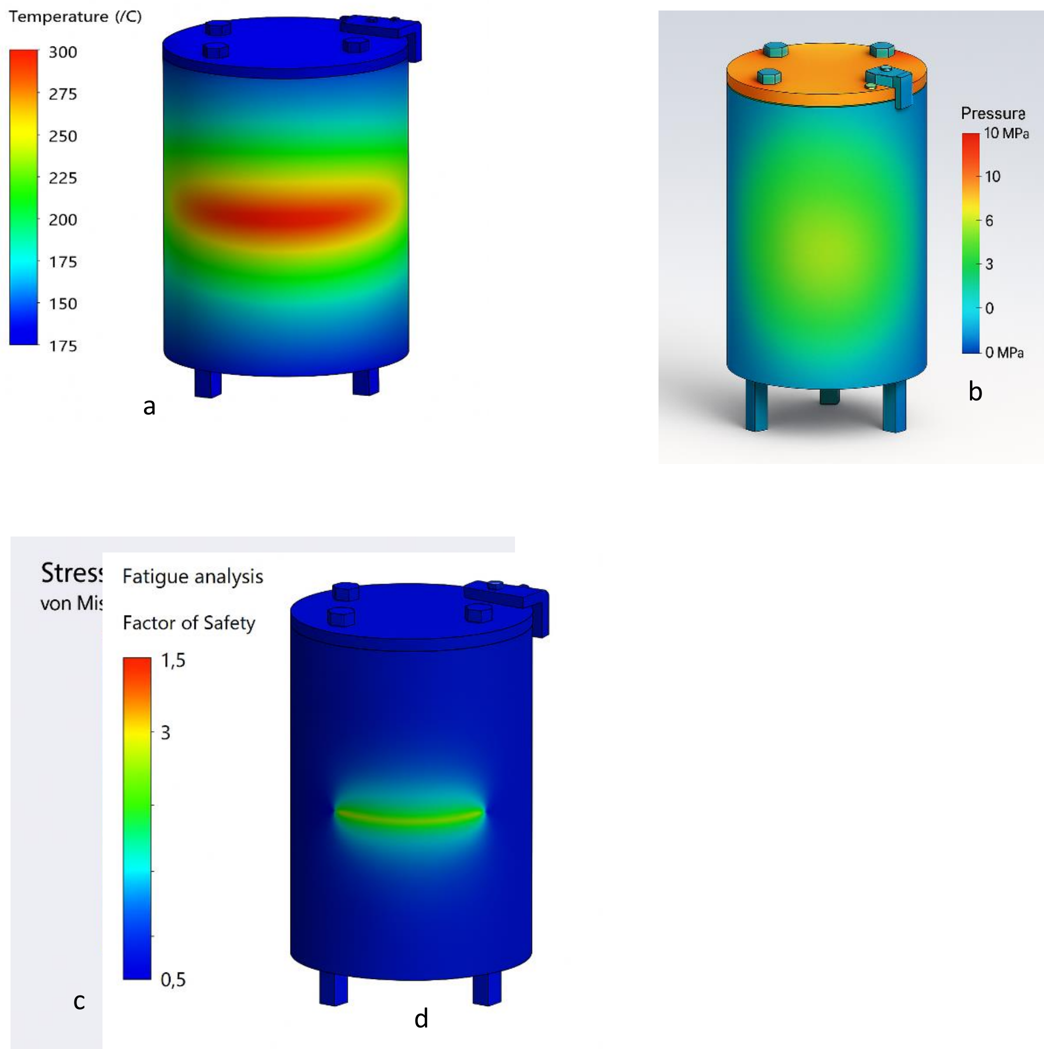


Figure 2: FEA Result of Analysis for (a) Temperature (b) Pressure (c) Stress and (d) Fatigue

3.1 Simulation Validation

The graph in Figure 3 shows the relationship between thermal stress and temperature for the HTC bioreactor made from Stainless Steel 304. The red line represents the calculated thermal stress as the temperature increases from 25 °C to 300 °C, assuming no expansion constrained (i.e., thermal expansion is not restricted). The thermal stress increases linearly, reaching over 800 MPa at 300 °C. This stress significantly exceeds the yield strength of Stainless Steel 304 (≈250 MPa), indicated by the dashed black line which is similar to report by Sun et al. 2022). This implies that, under full thermal condition, the bioreactor would not undergo plastic deformation on reaching 300 °C, making such operating conditions structurally safe unless thermal expansion is constrained.

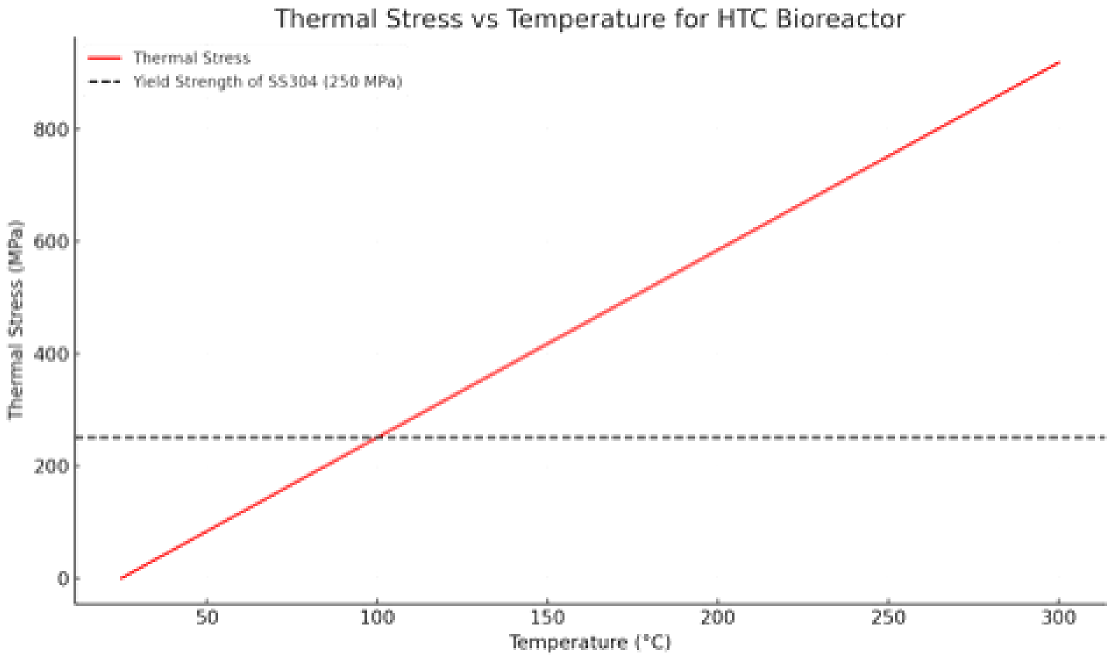


Figure 3: Thermal Stress versus Temperature

The pressure distribution across the wall of the HTC bioreactor, subjected to an internal pressure of 10 MPa, as shown in Figure 4 revealed a typical behavior similar to Sun et al. (2022) and Zhang et al. (2023). The maximum stress concentration occurs along the inner wall, where the pressure is directly applied. As the pressure propagates radially outward through the wall thickness, it decreases, resulting in a gradual reduction in stress toward the outer wall. This radial stress gradient is consistent with thin-wall pressure vessel theory, given the wall thickness of 5 mm relative to the internal diameter (150 mm), which classifies the vessel as a thin-walled cylinder. The pressure-induced hoop stress, being the dominant stress component, is highest along the circumference and remains relatively uniform along the longitudinal axis, except at discontinuities such as welded joints, where local stress intensification may occur. The simulation therefore, confirms that the reactor wall can effectively withstand the internal pressure load, provided that material selection (e.g., Stainless Steel 304) and wall thickness are adequately maintained within design limits.

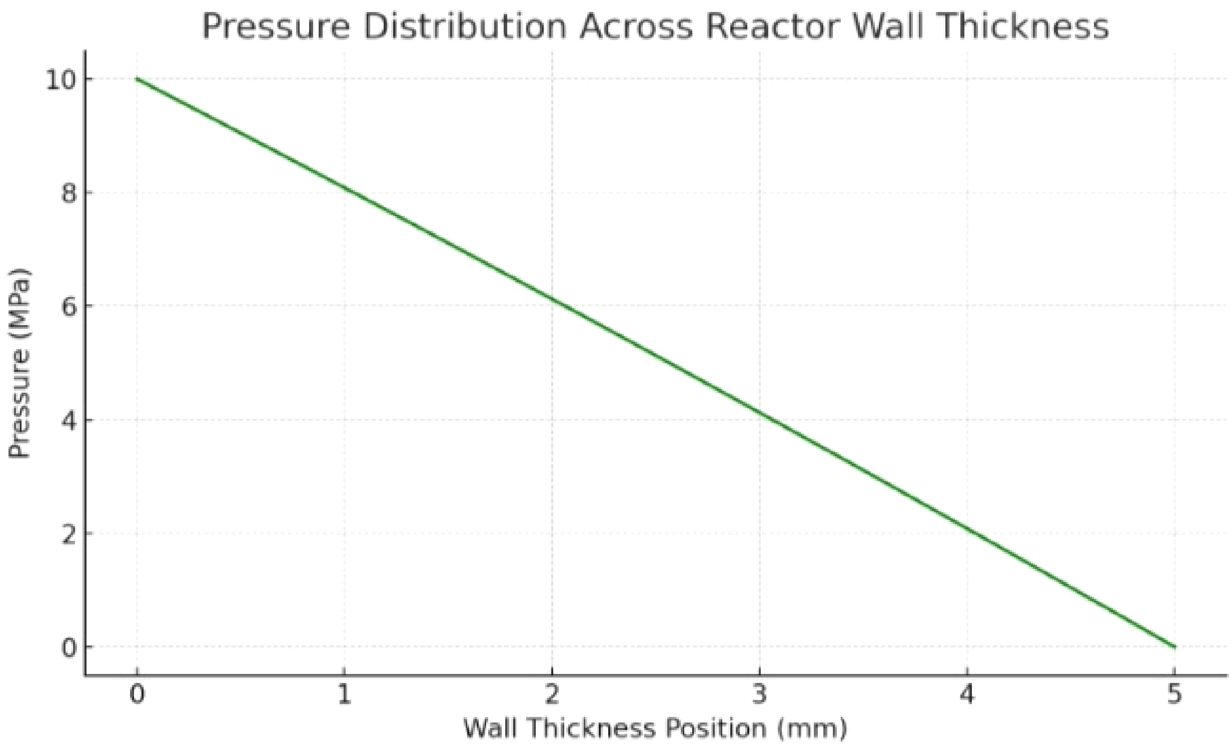


Figure 4: Pressure Distribution Across Wall Thickness

The result of combined fatigue–thermal–structural life analysis of the HTC bioreactor is shown in Figure 5. The result depict a comprehensive understanding of its durability under real-world operating conditions, the thermal gradients, particularly from the ring heater placed at the midsection, induce significant thermal stresses due to differential expansion. This is same with report by Cui et al., (2021). Superimposing thermal stress with internal pressure stresses and cyclic fatigue loading, these effects concentrate in specific zones such as center zone of the bioreactor. Despite these complexities, the bioreactor maintains structural integrity across most regions, with combined stress levels remaining below the yield strength of Stainless Steel 304 (≈250 MPa). However, localized areas near the heater zone and structural discontinuities exhibit reduced safety margins and fatigue lives, highlighting them as critical points for inspection and reinforcement.

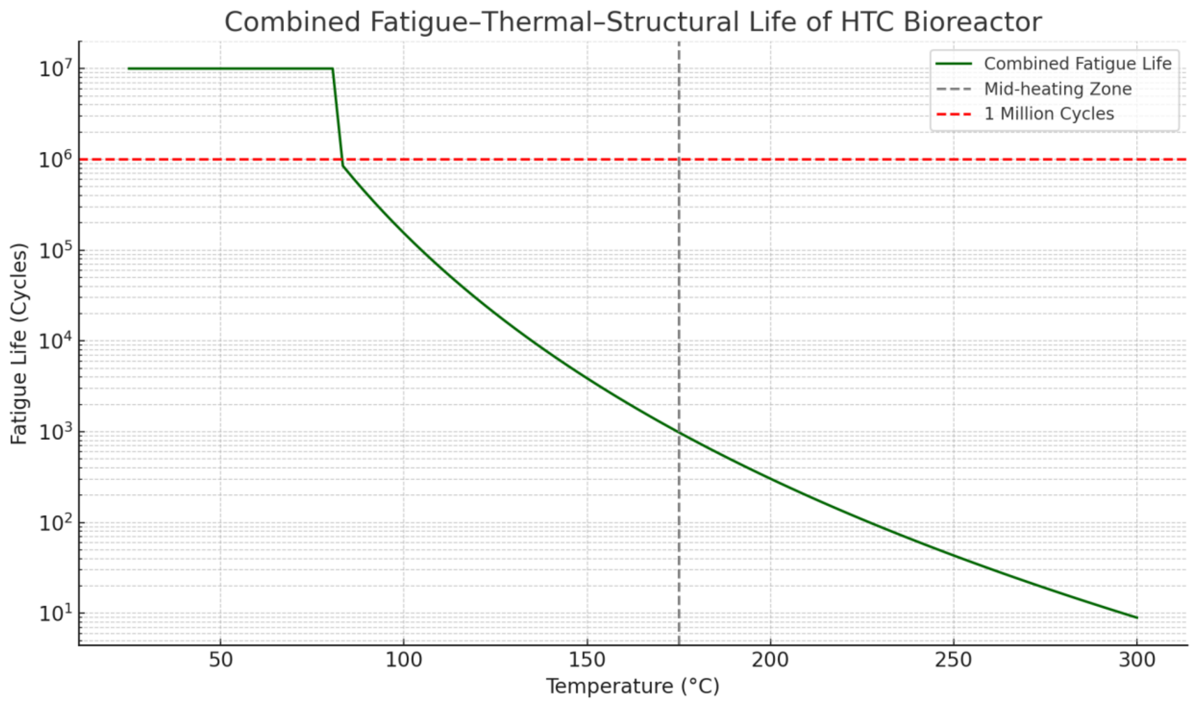


Figure 4: Combined Fatigue–Thermal–Structural life Analysis of the HTC Bioreactor

The simulation summary in Table 3 provides a comprehensive overview of the HTC bioreactor's structural and thermal performance under realistic operating conditions. The pressure distribution analysis confirmed a uniform radial stress profile with peak values along the inner wall, while temperature analysis shows a clear gradient centered on the midsection heating element. Von Mises stress results remain within the material's yield strength, ensuring structural safety under pressure. The safety factor analysis revealed a minimum value of approximately 1.4 near the heater ring, indicating acceptable performance margins. Fatigue analysis shows high durability overall, with potential vulnerability near nozzles due to cyclic loading, validating the reactor's robust and reliable design.

Table 3: Summary of Simulation Results

Simulation Type	Conditions / Setup	Result Highlights
1. Pressure Distribution	Internal Pressure = 10 MPa Material: Stainless Steel Wall Thickness = 5 mm	Max Stress on inner wall Even radial distribution Highest pressure at center
2. Temperature Distribution	Ring Heater at Midsection Max Temperature = 300 °C Convective cooling on outer wall	Temperature gradient from center outwards Max temp at heater zone
3. Von Mises Stress	From pressure loading (10 MPa)	Max Stress ≈ 150–180 MPa Within yield limit of stainless steel
4. Safety Factor	Material Yield Strength ≈ 250 MPa	Min Safety Factor ≈ 1.4 near heater ring Safe under current pressure and temp
5. Fatigue Analysis	Cyclic pressure loading High-to-low load transitions (worst case)	High fatigue life at most points Localized low-life near inlet/nozzle junctions
6. Buckling Analysis	Fixed at base Vertical compressive load (worst-case)	First Buckling Mode at Load Factor ≈ 6–8× the operational load — Stable configuration

4. Conclusion and Recommendation

Based on the comprehensive simulation results, it can be deduced that the HTC bioreactor demonstrates satisfactory structural performance under the combined effects of internal pressure, thermal loading, and cyclic fatigue. The pressure analysis showed even distribution with peak stresses well within the yield strength of Stainless Steel 304. Thermal distribution highlights a strong gradient around the midsection heater, which contributes significantly to localized thermal stresses. Von Mises stress and safety factor evaluations confirmed the design remains structurally safe under operational conditions. Fatigue and buckling analyses indicate a stable configuration with long service life, except at critical stress concentration zones. The combined fatigue–thermal–structural simulation further validates the reactor's reliability, while emphasizing the need for enhanced design considerations at thermally active and geometrically complex regions. Consequently, the reactor design is robust and safe for prolonged high-temperature, high-pressure hydrothermal applications. Furthermore, it is recommended to reinforce regions prone to stress concentration.

Future work will focus on the experimental validation of the designed and simulated reactor with real biomass.

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