Plastic Waste Pyrolysis Reactors with Integration of Rocket Stove and Advanced Heat Transfer System: An Analysis of its Design

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Abstract. The development of efficient and sustainable pyrolysis reactors is critical for advancing bioenergy technologies and waste management. This study presents the design and stress analysis of a pyrolysis reactor incorporating a rocket stove and an advanced heat transfer system, using Autodesk Inventor 2016. The integration of a rocket stove ensures efficient combustion and high-temperature stability, while the advanced heat transfer system maximizes thermal distribution within the reactor, enhancing the pyrolysis process. Stress analysis revealed critical stress points and informed design optimizations to ensure durability and safety. This innovative design approach, validated through advanced simulation tools, offers a significant advancement in the development of sustainable and efficient pyrolysis reactors. The safety factor is defined as the ratio of maximum allowable stress to equivalent stress. The permissible stress value for stainless steel components used in pyrolysis tubes is 187.5 MPa. The stress analysis test revealed that the reactor tube experienced a maximum equivalent stress of 17.72 MPa. The reactor's design, incorporating materials capable of withstanding high temperatures and stresses, ensures safe and reliable operation. Stress analysis and the implementation of appropriate safety factors play a critical role in maintaining the reactor's structural integrity.

1 Introduction

The growing accumulation of plastic waste poses significant environmental challenges, necessitating innovative solutions for effective waste management and resource recovery. Pyrolysis, a thermochemical process that decomposes organic materials in the absence of oxygen, offers a promising method for converting plastic waste into valuable products such as bio-oil, syngas, and char [1]. However, optimizing the efficiency and sustainability of pyrolysis reactors remains a critical area of research and development [2].

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Pyrolysis is a versatile thermochemical process that decomposes organic materials in the absence of oxygen, leading to the production of various valuable byproducts such as bio-oil, syngas, and char. This process occurs at elevated temperatures, typically between 300°C and 800°C, and involves the thermal breakdown of complex organic molecules into simpler compounds [3]. Pyrolysis has garnered significant attention in recent years due to its potential applications in waste management, renewable energy production, and the development of sustainable materials. The primary advantage of pyrolysis lies in its ability to convert a wide range of feedstocks, including biomass, agricultural residues, and plastic waste, into useful products. This capability makes it an attractive solution for addressing the global challenge of waste accumulation and resource depletion. By transforming waste materials into energy-rich products, pyrolysis not only mitigates the environmental impact of waste disposal but also contributes to the circular economy by recovering valuable resources [4, 5].

One of the key drivers behind the growing interest in pyrolysis is the increasing need for alternative energy sources. As fossil fuel reserves dwindle and environmental concerns about greenhouse gas emissions intensify, pyrolysis offers a promising pathway for producing renewable biofuels and reducing reliance on conventional energy sources. Additionally, the byproducts of pyrolysis, such as biochar, have significant applications in soil improvement and carbon sequestration, further enhancing the environmental benefits of this technology. Despite its potential, the efficiency and scalability of pyrolysis processes depend heavily on the design and optimization of the reactors used. Effective heat transfer, temperature control, and feedstock management are crucial factors that influence the overall performance and economic viability of pyrolysis systems [6]. Advanced reactor designs that incorporate innovative heat transfer mechanisms and efficient combustion systems, such as rocket stoves, are essential for maximizing the yield and quality of pyrolysis products. This introduction underscores the importance of continued research and development in pyrolysis technology to harness its full potential. By advancing reactor design and optimizing process parameters, pyrolysis can play a pivotal role in sustainable waste management, renewable energy production, and environmental conservation [7].

The principles of reuse, reduce, and recycle are essential strategies for sustainable waste management and environmental conservation [8]. Reuse encourages finding new ways to utilize items that might otherwise be discarded, such as repurposing containers, donating used goods, and extending the life of products through creative applications. Reduce focuses on minimizing waste generation by making mindful decisions about consumption, such as buying products with less packaging, opting for durable items, and purchasing only what is necessary. Recycling involves collecting, processing, and converting waste materials into new products, thus conserving natural resources, saving energy, and reducing pollution. Together, these principles help to minimize waste, conserve resources, and mitigate the environmental impact of human activities, promoting a more sustainable and responsible approach to consumption and waste management [9].

A Process flow diagram (PFD) of a pyrolysis system illustrates in Figure 1, outlines the sequential steps involved in converting feedstock into valuable products such as bio-oil, syngas, and biochar through thermal decomposition in the absence of oxygen. It typically begins with feedstock handling and pretreatment, including drying, size reduction, and sorting to optimize the process [10]. The prepared feedstock is then fed into the pyrolysis reactor, where it undergoes thermal decomposition under controlled conditions. A heat source is employed to initiate and sustain the pyrolysis reaction. After pyrolysis, the products are recovered and separated, with bio-oil, syngas, and biochar being the primary outputs. Gas cleaning processes may be implemented to remove impurities from the syngas, while bio-oil may undergo further refining to enhance its quality. Biochar, the solid residue, can be processed and utilized for various applications. Proper product storage and handling are crucial before distribution or further utilization. Overall, the PFD illustrates the essential steps involved in the pyrolysis process, emphasizing feedstock preparation, thermal decomposition, product recovery, and post-processing techniques to maximize the efficiency and yield of valuable products [11, 12].

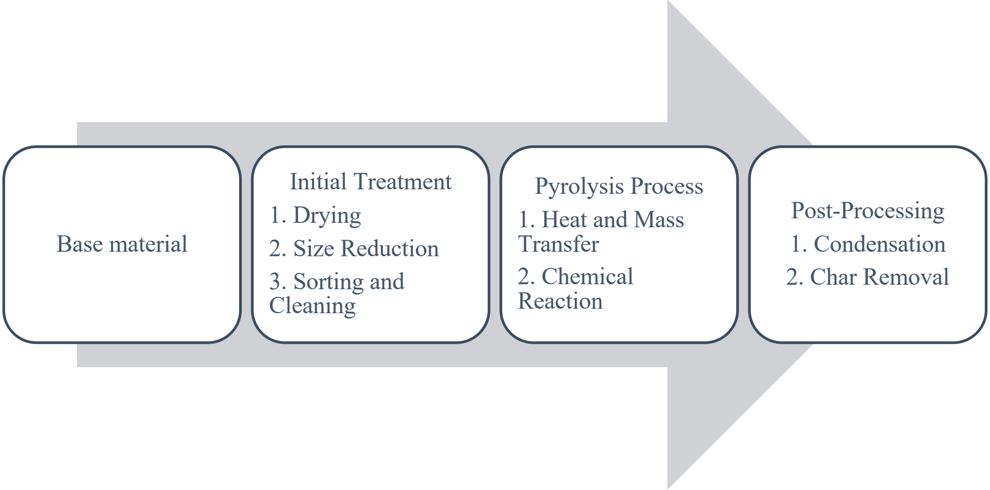

Fig. 1. Process flow diagram of a pyrolysis.

This study focuses on the design analysis to ensure the reactor's safety, durability, and reliability under high-temperature operations, ultimately contributing to a more sustainable solution for plastic waste treatment. The integration of a rocket stove and advanced heat transfer system represents a significant innovation in pyrolysis reactor technology, aiming to enhance energy efficiency, improve product yield, and reduce environmental impact. This research contributes to the development of more sustainable and effective methods for plastic waste management, aligning with global efforts to address the environmental crisis posed by plastic pollution. Meanwhile, the advanced heat transfer system ensures uniform temperature distribution within the reactor, optimizing the thermal decomposition of plastic materials [13]. By employing cutting-edge tools such as Autodesk Inventor 2016, we conducted comprehensive 3D modelling to assess the structural and thermal performance of the reactor design. This approach allows for precise evaluation of stress distribution and thermal efficiency under operational conditions, ensuring the reactor's durability and effectiveness.

2 Methodology

Pyrolysis, a thermochemical decomposition of organic materials in the absence of oxygen, has been extensively studied and applied in various fields due to its potential for waste management and energy recovery. Significant research has focused on optimizing pyrolysis processes for different types of feedstocks, including biomass, agricultural residues, and plastic waste.

One of the most widely studied applications of pyrolysis is the conversion of biomass into bio-oil, syngas, and biochar. Lee et al. (2020) explored the production of bio-oil from various types of biomasses and highlighted the importance of feedstock properties, reactor design, and operating conditions on the yield and quality of the products [14]. More recent studies by Rahman et al. (2018) have investigated the catalytic pyrolysis of biomass to enhance the quality of bio-oil and improve process efficiency [15, 16]. The pyrolysis of plastic waste has gained attention as a method for mitigating the environmental impact of plastic pollution. Jahirul et al. (2022) reviewed different pyrolysis techniques for plastic waste, emphasizing the potential of pyrolysis to produce valuable hydrocarbons that can be used as fuel or chemical feedstocks [17]. A study by Kazawadi et al. (2021) demonstrated the feasibility of converting mixed plastic waste into liquid fuels, highlighting the influence of temperature and catalyst type on product distribution [18].

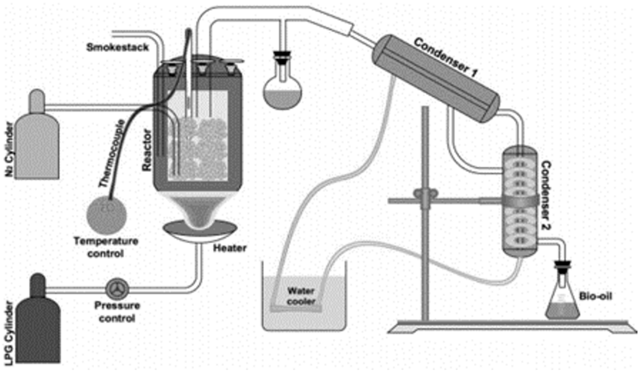

Fig. 2. Design of pyrolysis reactor for production of bio-oil [17].

In addition, researchers studied the impact of pyrolysis temperature and duration on ash content, concluding that an increase in pyrolysis temperature led to an increase in ash content depicted in Figure 2. The large amount of hydrocarbon *C* in the pyrolysis results is the main cause. The number of *C* atoms has an impact on the amount of ash content. As the number of *C* atoms increases, so does the ash content. Ash is the result of the oxidation reaction of unconverted *C* atoms. The higher the heating temperature during the pyrolysis process, the more complete the decomposition of the substances contained in plastic will be [19]. These substances will decompose into gas and oil.

2.1 Design and Systematics of Research

The design of pyrolysis reactors features a shell, a vertical cylindrical cross-section. The head, which is the reactor end cap, was chosen to remain flat to reduce manufacturing costs, ensure easy maintenance, and allow a greater degree of heat transfer. Pyrolysis reactors are designed with a vertical cylindrical cross-section shell. The decision to keep the head, serving as the reactor end cap, flat was made to minimize manufacturing expenses, facilitate maintenance, and enhance heat transmission capabilities.

The reactor is specifically engineered to function under standard atmospheric pressure conditions. Specific locations are designated for the installation of pressure gauges, the connection of pipelines to drive steam towards the condenser, and the removal of charcoal [20]. Chemical processing industries mostly use condenser shells and tubes for steam condensation processes. Researchers design condenser shells and tubes with very little inclination to the horizontal for experimentation, facilitating proper support and allowing liquid oil to flow naturally under gravity for easy collection [21].

The reactor and conical cover are sealed with asbestos gaskets and high temperature silicone. Ultimately, nuts and bolts serve the purpose of joining them together. A sensor for detecting temperature is put into the reactor through the feed hole using an electrical device [22]. The condenser shell, baffle, and cover plate are constructed from mild steel. Tubes made of copper are organized in tube sheets and subsequently joined together by soldering to create tube bundles. Gaskets and high temperature silicone are employed to create an airtight seal between the cover plate and condenser shell.

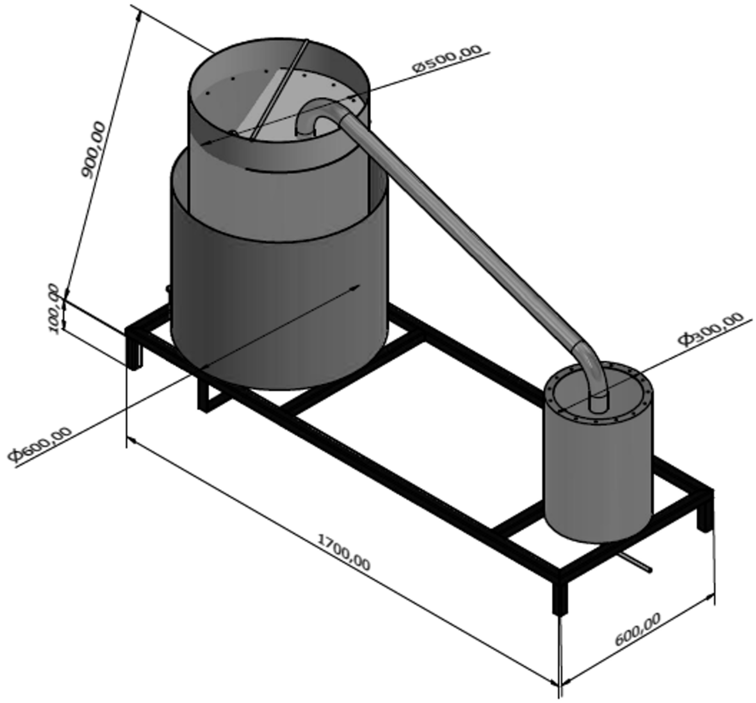

Fig. 3. The design of pyrolysis reactor.

The dissolution tank employs an innovative solvent to effectively dissolve polyolefin plastic waste at a temperature of 240°C, resulting in the creation of a uniform liquid feed. The liquid feed is introduced into the pyrolysis reactor at a maximum flow rate of 1 kg/h. Primary pyrolysis takes place at a temperature of 460°C in heating zone 1. During primary pyrolysis, the polyolefin plastic undergoes a process in which it is decomposed into hydrocarbons of different chain lengths through a mechanism of random breaking of chemical bonds [7].

The design of pyrolysis reactor depicted in Figure 3, to produce pyrolysis oil and char from plastic waste. This tool has a reactor volume that is predicted to be able to process 10 kg of plastic. The reactor features a cylindrical, batch type design, with a fixed reactor seat. The reactor's top can be opened to load raw materials and easily remove the biochar at the conclusion of the experiment. A thermocouple monitors the internal temperature of the reactor, while a securely fastened cover ensures that the top remains sealed during the pyrolysis process, preventing air from entering and maintaining optimal conditions. The reactor weighs around 20-30 kg and is insulated to minimize heat loss. At the bottom of the reactor, a pressurized gas stove is positioned to regulate temperature variations. The stove also provides two volatile condensers for capturing the volatile gases, which are condensed into bio-oil or pyrolytic oil. Cold water circulating around the tube helps condense the hot gas as it passes through the inner condenser tube.

The pyrolysis tool is positioned on a frame that is specifically constructed to allow for the adjustment of the placement of its components. These components include a reactor, air condenser, water condenser, connecting pipe, water pump, and burner. To enhance portability, wheels have been incorporated into the design of this instrument, with each leg of the frame equipped with its own set of wheels. In addition, a plate was installed as an insulator to prevent the spread of gusts of wind and fire to other components.

The designed pyrolysis reactor has a simple design and easy maintenance. In addition, the reactor system does not have complicated component requirements. The pyrolysis equipment's design is based on considerations of the pyrolysis system concept. The systematics of research on design and stress analysis can be seen in Figure 4.

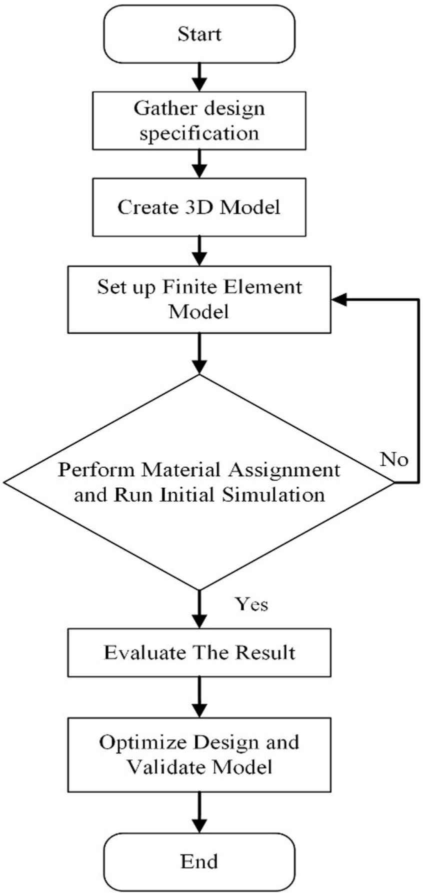

Fig. 4. Research flowchart.

2.2 Stress Analysis Process

A stress analysis flowchart for a pyrolysis reactor provides a systematic representation of the essential activities involved, starting from identifying objectives in the first phase and concluding with the execution of optimum designs. The procedure commences by delineating the objectives and scope to determine the aims of the study and identify the reactor components to be assessed. Subsequently, comprehensive design specifications are collected, encompassing material attributes and operational circumstances. Subsequently, a comprehensive three-dimensional representation of the reactor is generated utilizing an Autodesk Inventor. The imported model is utilized in finite element analysis (FEA) software, where specific meshing settings and suitable element types are established [17]. The model is subjected to boundary conditions and operating loads, including thermal loads and pressure.

Each component is assigned material properties according to the design criteria. A preliminary simulation is performed to detect areas of high stress and crucial points. The findings are assessed to identify any stress values that surpass the material limits or design standards. If deemed required, adjustments are made to the reactor design to resolve any identified stress-related concerns. Subsequently, the amended design undergoes multiple iterations of simulation. The accuracy of the model is verified by comparing it to experimental data or information from published sources. A thorough documentation and reporting of the analysis process and findings are created, encompassing recommendations and conclusions. Ultimately, the refined design is put into practice in the real manufacturing process of the reactor, with ongoing monitoring of its performance to assure its efficacy. By employing this methodical approach, every crucial element of stress analysis is considered, resulting in a robust and effective design for the pyrolysis reactor.

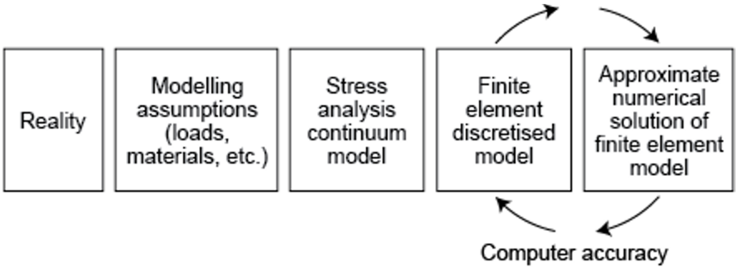

Fig. 5. Reality of the finite element model [12].

Figure 5 presents a horizontal block-type flow diagram that outlines the five-step progression from reality to the modelling phase. Starting from the left with reality, the steps include modelling assumptions (such as loads and materials), the stress analysis model, the finite element discretized model, and the approximate numerical solution of the finite element model. Four curved arrows indicate that the computer accuracy phase focuses solely on the last two blocks. In developing an instrument for fuel oil production from plastic bottle waste, stress analysis is performed using Autodesk Inventor software. The analysis considers constraints, materials, and loads. The results of the stress analysis are then reviewed and discussed in the subsequent phase.

3 Results and Discussion

The stress analysis of a pyrolysis reactor tube provides crucial insights into the mechanical performance and structural integrity of the reactor under operational conditions. The analysis typically involves evaluating the distribution and magnitude of stresses and identifying potential areas of concern that could impact the reactor's longevity and safety. The results often reveal specific regions within the reactor tube where stress concentrations occur. These high-stress areas are found around discontinuities such as weld joints, bends, and points of attachment for other components. In the analysed pyrolysis reactor tube, significant stress concentrations were observed near the inlet and outlet sections, where the temperature gradients are steepest and mechanical loads are highest. Such areas are critical as they are prone to fatigue and failure over prolonged use.

The current step involves determining the reference position of the support constraints and loads in the design that has been constructed. The process of determining constraints involves multiple distinct steps, including reactor limitations, air condenser constraints, water condenser constraints, frame constraints, and total pyrolysis equipment restrictions that can see in Table 1 and Table 2.

Table 1. Reactor specification.

Name	Stainless Steel	
General	Mass Density	8 g/cm^3
	Yield Strength	250 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	193 GPa
	Poisson's Ratio	0.3
	Shear Modulus	74.23 GPa

Table 2. Frame specification.

Name	Stainless Steel	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	210 GPa
	Poisson's Ratio	0.3
	Shear Modulus	80.77 GPa

Given the high-temperature environment of pyrolysis reactors, thermal stresses play a significant role in the overall stress profile. The analysis showed that the thermal expansion and contraction cycles lead to cyclic thermal stresses, which can contribute to the development of thermal fatigue. The inner surface of the reactor tube, in contact with the hot pyrolysis gases, experiences the highest thermal stresses. It is essential to ensure that the material used for the reactor tube can withstand these stresses without significant degradation over time.

The stress analysis results must be compared with the material's yield strength and ultimate tensile strength to assess the safety margin. In this case, the maximum stress observed in the reactor tube was within acceptable limits for the chosen material, a high-temperature alloy known for its strength and resistance to thermal fatigue. However, the safety margin was narrow in some regions, suggesting the need for careful monitoring and potential design improvements. The current step involves determining the reference position of the support constraints and loads in the design that has been constructed. The process of determining constraints involves multiple distinct steps, including stress analysis in reactor tube of pyrolysis (Table 3).

Table 3. Stress analysis in reactor tube of pyrolysis tool.

Name	Minimum	Maximum
Volume	3165340 mm^3	
Mass	25.3227 kg	
Von Mises Stress	0.0000442384 MPa	17.72 MPa
1st Principal Stress	-2.91904 MPa	16.47 MPa
3rd Principal Stress	-13.6745 MPa	2.51856 MPa
Displacement	0 mm	0.0238962 mm
Safety Factor	14.1084	15

The results of the stress analysis are in Figures 6-8 which consist of von Misses stress images, displacement images, and safety factor images.

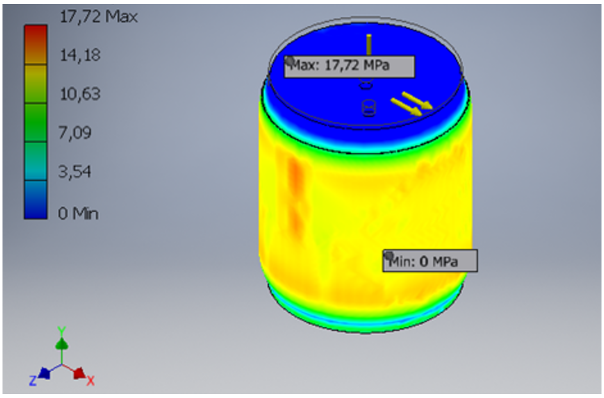

Fig. 6. Von mises stress reactor tube.

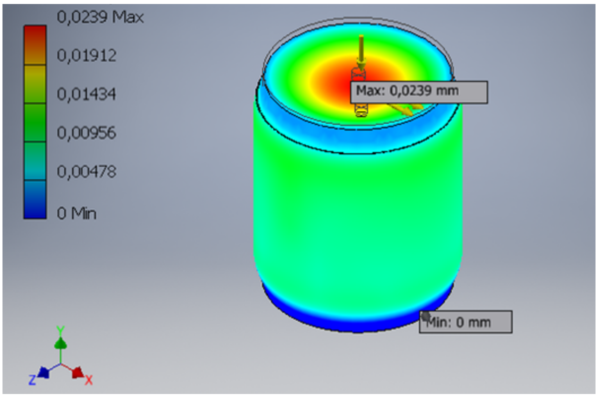

Fig. 7. Displacement of reactor tube.

The reactor cover reached a peak equivalent stress of 17.72 MPa depicted in Figure 6. The simulation findings demonstrate that the design undergoes deformation when exposed to external force. The central part of the reactor lid, which was connected to the pipe with a gap of 0.0239 mm, exhibited the highest deformation magnitude (Figure 7). Conversely, the reactor base experiences the least amount of deformation, at 0.0 mm. The minimum deformation value is situated in proximity to the fixed restriction. A safety factor is a measure used to determine the amount of safety in a design. Based on the simulation results, the minimum safety factor is 14.108 in Figure 9, while the maximum safety factor is 15. A design is deemed safe when the safety factor value exceeds 1.

The safety factor in the reactor tube of a pyrolysis system is a crucial design parameter that ensures the structural integrity and safe operation of the reactor under various conditions. It is defined as the ratio of the material's maximum allowable stress to the actual stress experienced during operation (Figure 8). This factor accounts for uncertainties in material properties, manufacturing imperfections, unexpected loads, and other unforeseen conditions, providing a margin of safety to prevent structural failure. In designing the reactor tube, engineers perform detailed stress analysis to determine the stresses from thermal expansion, internal pressure, and mechanical loads. Using the material's yield strength or tensile strength, they calculate the safety factor, ensuring it meets or exceeds industry standards and safety requirements.

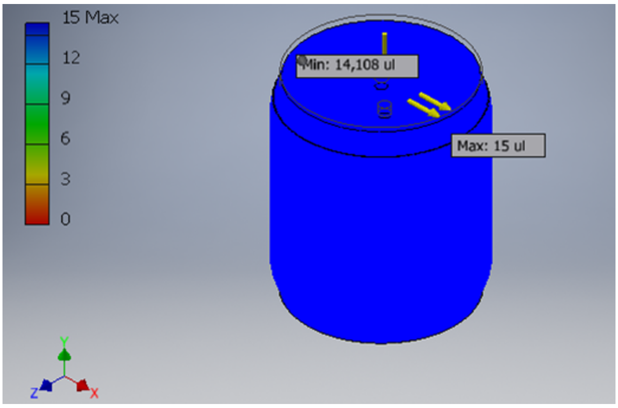

Fig. 8. Safety factor in a reactor tube.

4 Conclusions

The analysis highlighted opportunities for optimizing the reactor tube design to reduce stress concentrations and enhance durability. Possible design modifications include increasing the wall thickness in high-stress areas, using smoother transitions at bends and joints to minimize stress risers, and incorporating thermal insulation or cooling mechanisms to manage temperature gradients more effectively. Implementing these changes can reduce the likelihood of mechanical failure and extend the reactor's operational life.

If the maximum value exceeds the strength of the material (allowable stress), Von Misses stress fails. The safety factor is defined as the ratio of maximum allowable stress to equivalent stress. In the context of ultimate strength, we typically express the maximum principal stress as a safety factor ratio. For the design to be deemed practical, the safety factor value must surpass one. The permissible stress value for stainless steel components used in pyrolysis tubes is 187.5 MPa. The stress analysis test revealed that the reactor tube experienced a maximum equivalent stress of 17.72 MPa. According to the stress analysis report, the maximum equivalent stress value for stainless steel pyrolysis reactor tube components is smaller than the allowable stress. Therefore, it can be concluded that the design of the pyrolysis tool made from stainless steel is declared to have passed according to the criteria of the American Institute of Steel Construction (AISC).

To validate the stress analysis results, experimental testing under simulated operational conditions is recommended. This validation can confirm the accuracy of the simulation and provide additional data for refining the analysis model. Future work could also explore alternative materials with higher thermal and mechanical resilience and investigate advanced manufacturing techniques that might improve the structural integrity of the reactor tube. The stress analysis of the pyrolysis reactor tube provides a comprehensive understanding of the mechanical stresses encountered during operation. By identifying high-stress areas and comparing the stress levels with material properties, the analysis informs necessary design improvements and maintenance strategies. Ensuring the reactor's structural integrity through such analysis is crucial for safe, efficient, and reliable pyrolysis operations, contributing to the technology's broader adoption in waste management and energy production.

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