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Școala Doctorală de Inginerie Industrială și Robotică

SUMMARY PHD THESIS

Theoretical and experimental contributions regarding the design and realization of a nuclear microreactor vessel through additive manufacturing technologies

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Chapter 1. Introduction

1.1 Introduction

Through the following chapters, the research addresses topics in additive manufacturing, CAD (computer-aided design), nuclear engineering, reactor physics and mechanical properties of the materials used. Having such diverse topics requires collaboration and support from multiple disciplines. The final product resulting from the work presented in this thesis may need further refinement to achieve operational status. The purpose or initial goal of the thesis is the design of a microreactor containment vessel that can provide 2MW(Megawatts) electric and demonstrate that it may be a feasible product for operation. A nuclear reactor is the equipment that produces heat using fission or fusion. The nuclear fission process heats the primary heat transport system that may contain water or other cooling agents. The working fluid is selected based on design and technology considerations [1] [2]. The nuclear industry has relied on technologies developed in the 1950s, however, there is an opportunity to integrate new methodologies with demonstrated nuclear reactor principles. Additive manufacturing (AM) represents one of the opportunities for improvement as it offers flexibility and efficiency improvements over traditional manufacturing processes. The next chapters will describe the process for developing a microreactor containment vessel's conceptual design, thermal analysis, and the analysis of specific materials used for additive manufacturing.

In the analysis stage of literature review it came up more than once that microreactor containment vessel design and manufacturing processes have several challenges such as size constraints, material selection, and thermal management. Traditional manufacturing methods have limits that may affect the complexity and efficiency of reactor designs or require refinements. This research addresses these challenges by considering additive manufacturing to develop a compact and as efficient as possible microreactor containment vessel capable of safely managing the thermal output of a nuclear microreactor.

The objective is to develop a conceptual design for a nuclear microreactor containment vessel that can be manufactured through additive manufacturing. Going into more detail, the study performed includes identifying the optimal design parameters and materials for the containment vessel, evaluating the thermal performance of the design samples that are representative of the models, under various operational conditions using computational fluid dynamics (CFD), and assessing the feasibility of different additive manufacturing techniques for producing the containment vessel and validation of the selected material to be used for manufacturing of the proposed concept.

To meet the research objectives, the study will start with exploring questions regarding what are the primary design considerations for manufacturing a nuclear microreactor containment vessel using additive techniques, how the thermal performance of the designed vessel compares under different operational scenarios and which additive manufacturing techniques are most suitable for producing the containment vessel, taking into account factors such as material properties, manufacturing precision, and cost. The study goes further and analyses the behaviour of the material properties after the AM process through tensile and stress tests, and how the properties of the selected material behave in an irradiated environment.

1.1.1 Additive Manufacturing Considerations

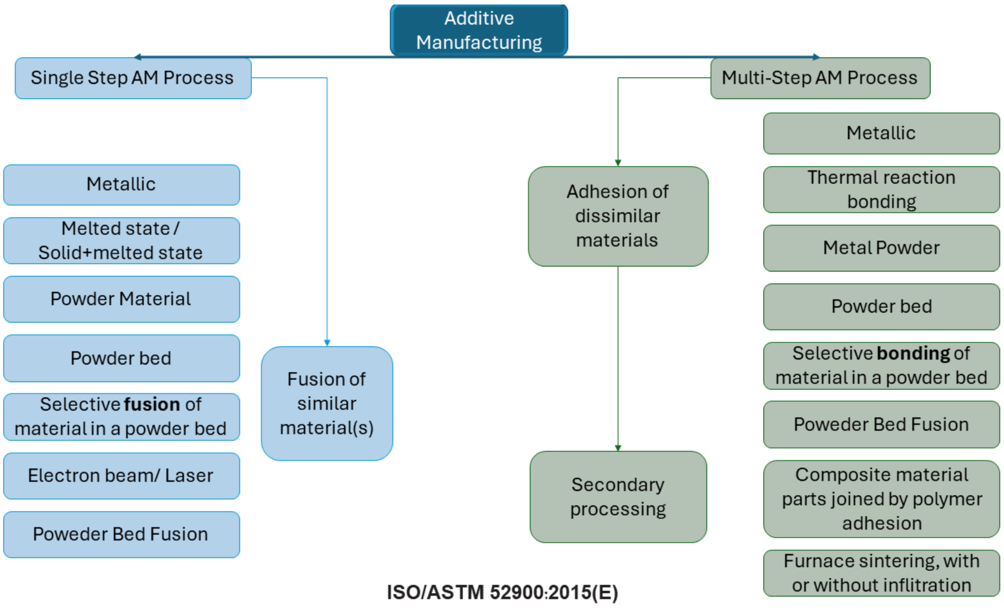
Additive Manufacturing (AM) is the process of building objects, layer by layer from a digital source that describes the model of the object [3]. AM offers several benefits in the design and manufacturing process as it may create complex geometries which offers more design freedom than traditional manufacturing methods and may facilitate a smooth production process eliminating uncertainties from the nuclear supply chain. The nuclear industry, characterized by its strict requirements for safety, reliability, and performance, is increasingly exploring the application of AM for fabricating components [4]. Most published literature for additive manufacturing of metals discusses stainless steel 316L and explores designs and lattice structures that improve heat transfer parameters [4]. Considering AM parts were previously used in nuclear facilities [5], fabricating a containment vessel is the next step in testing the limits of AM in the nuclear field.

According to Ehsan et. al. [6], ISO/ASTM [7] catalogued 3D printing technologies into seven groups, with the exception of vat photopolymerization (VPP), the rest of the AM technologies may be used for metal manufacturing and as indicated by Ehsan [6], the order of the technologies is indicative of their popularity.

The technologies and materials used in the nuclear energy sector need to be properly verified and validated to ensure that they meet the requirements for safety, security, and reliability for operating in such an environment. There are other considerations such as corrosion resistance, mechanical strength, durability, and proper control of the fabrication process parameters including post-processing that need to be addressed.

Powder Bed Fusion encompasses Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Both techniques use a high-energy beam to fuse metal powders layer by layer.

One of the requirements when optimizing a model for AM is topology optimization, as described by Carsten et. al. [8] with promising results. A disadvantage of SLM, as identified by Kruth et. al. [9], is residual stress and cracking which may be mitigated by high preheat temperature and using short scan vectors.



ISO/ASTM 52900:2015(E)

Figure 1.1 AM fabrication process for metals as interpreted from ISO/ASTM 52900:2015

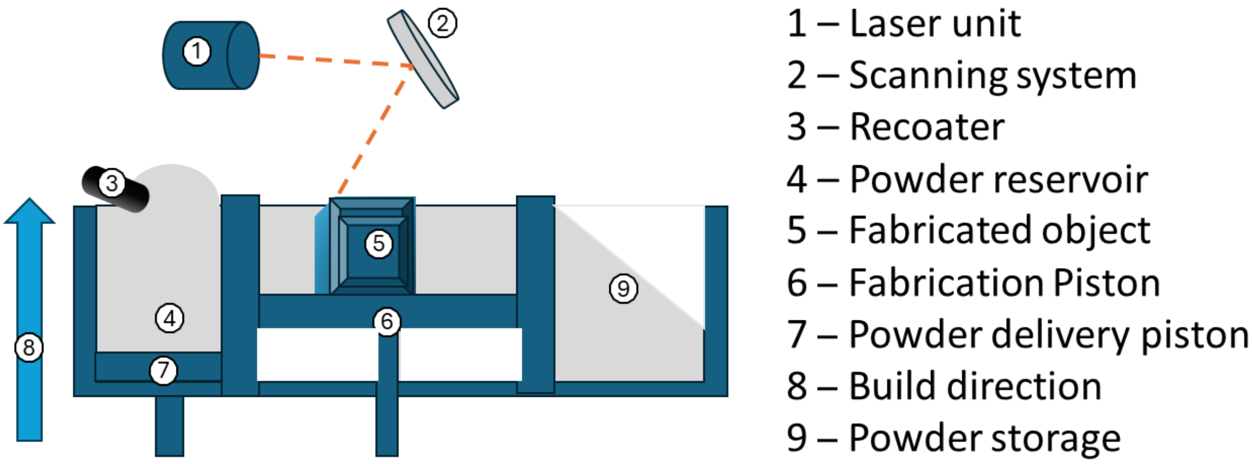


Figure 1.2 Interpretation of SLM manufacturing process schematic *[10]*

After selecting Stainless steel 316L as the primary material for manufacturing the reactor containment vessel through the SLM process Figure 1.2, we can move forward to the next stages of our initial hypothesis. The material properties were taken from a manufacturer [11] to be as close as possible to the real material parameters encountered in the market. We will use these values in the design and simulation software stages.

1.2 Research methodology and technology integration

The thesis methodology implies at least 5 high level stages of work that needs to be performed as presented in Table 1.1 and in Figure 1.3.

Table 1.1 Research Methodology

Methodology Stages	Subtopics
1. Literature Review	•Relevant articles discussing additive manufacturing, materials analysis, and their use in the nuclear industry.
	•Books relevant to the purpose of the thesis.
	•Relevant publications from national and international organizations in nuclear and additive manufacturing.
2. CAD Design	•Choice of software: ANSYS SpaceClaim, ANSYS CFD/Fluent, ANSYS Workbench.
	• Designing 3D models – Iterative process.
	•Assembling 3D components and identifying compatible models.
3. Thermal analysis	• Overview of thermal management
	• Identifying and simulating the environment in which the vessel must operate.

	• Identification of results from literature analysis and comparison.
	• Conclusions and future steps forward.
4. Testing of Materials	• Tensile testing of materials.
	• SEM analysis.
	• Post-irradiation analysis of the material.
5. Validation and Benchmarking	• Comparison of the results with parameters encountered in the specific conditions of a nuclear reactor.
	• Corrective actions to improve the model.

All identified stages are interconnected and feed into each other at every step of the research methodology. This iterative manner is due to the complex nature of the research, involving additive manufacturing, nuclear technologies, thermal analysis, CAD design and experimental setup for validation and testing of environments.
One important aspect is that although the literature review stage is presented at the beginning of this thesis, it is present in each stage and results feed into changes in approaches for both literature review and next research stages.

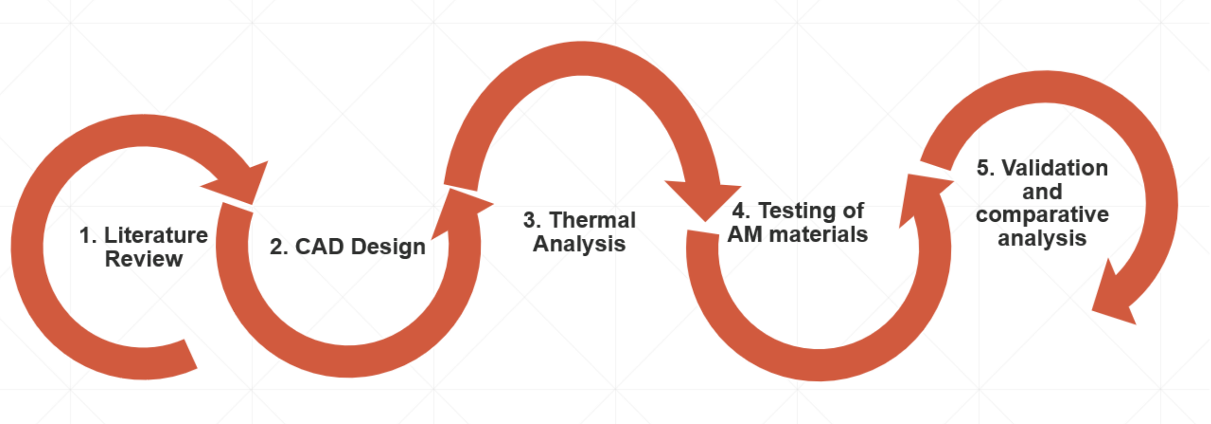


Figure 1.3 Research Methodology

Combining additive manufacturing with nuclear microreactors is a new approach that shows promise to change the design and manufacturing of components for nuclear technology applications. Being operated in isolated applications such military outposts, space activities, or towns without access to the main electrical grid, nuclear microreactors are good alternatives for creating safe and dependable energy. Modern production technology known as additive manufacturing, sometimes referred to as 3D printing, lets components be created by successive material additions, so enabling the realisation of intricate and customised geometries not possible with conventional manufacturing techniques.

These two disciplines taken together provide a number of benefits, first of all, AM lets component design for microreactors to be optimised, therefore improving the performance of the system generally. By means of maximising heat transport and optimising the cooling flow inside the reactor, unconventional shapes help to guarantee more homogeneous temperature distribution and more effective operation. By means of AM techniques, for instance, cooling channels with ideal forms can enhance heat management and lower the chance of hot spot development without compromising reactor safety.

AM also provides more control over the microstructure of materials, which is important in the framework of nuclear microreactors running in radiation and high temperature conditions. By customising materials generated by AM to have certain mechanical and strength characteristics, one guarantees better response to running circumstances. Furthermore, this process minimises the number of joints and welds needed to assemble the components, thereby lowering the chance of structural flaws and cracking, and so improving the reactor's reliability.

Furthermore, the corelation of AM with nuclear microreactors has economic benefits, such as the fast adaptation of projects depending on the particular needs of every reactor, made possible by the increasing efficiency of the manufacturing process, which also helps to lower the time needed for component development. Microreactors' progress depends on this adaptability to fulfil various application requirement, and additive manufacturing presents the means to customise every reactor based on the requirements of the site of installation, so enhancing the general reliability and efficiency.

The combination of additive manufacturing with nuclear microreactors offers a potential solution for the direction of nuclear energy, therefore helping to overcome present constraints of conventional manufacturing techniques. This mix offers a workable answer for the energy demands of the 21st century since it enables the optimisation of design, the enhancement of material performance, and the potential building of more efficient and safe reactors.

1.3.1 Identified improvement activities in existing literature

Several improvements may be implemented in future activities, one such improvement is the need for more comprehensive characterization techniques to understand the microstructure and mechanical properties of AM materials used in nuclear applications. AM processes can lead to anisotropic textures and heterogeneities, which affect mechanical properties such as tensile strength and fatigue behaviour [12], further research is needed to optimize process parameters and heat treatment strategies to align the properties of AM materials with those of conventionally manufactured materials.

The lack of specific standards for AM materials in nuclear applications is a significant gap. While there are standards for other industries, nuclear applications require tailored standards to ensure safety and reliability [13].

AM processes can introduce defects such as porosity and residual stresses, which can compromise the safety of nuclear components. More research is needed to develop methods for defect detection and mitigation to ensure the integrity of AM-manufactured components [14] [13].

The behaviour of AM materials under irradiation conditions represents a critical factor in nuclear environments, is not well understood. Studies on irradiation damage behaviours and the long-term performance of AM materials in nuclear reactors are necessary.

The qualification and certification of AM components for nuclear applications are still in their early stages. There is a lack of well-established processes and standards for certifying AM components, leading to high costs and prolonged lead times. Developing a robust framework for qualification and certification, similar to those in aerospace, is crucial for the adoption of AM in nuclear applications.

Efforts to integrate AM into existing nuclear codes and standards are ongoing, but more work is needed to establish comprehensive regulatory frameworks that address the unique challenges of AM [15].

The energy efficiency of AM processes in nuclear applications is not well-documented. There is a lack of standardization in measuring and reporting energy consumption, which hinders the evaluation of AM.

Chapter 2. Conceptual Design of a Microreactor-Containment Vessel: Requirements and Specifications

2.1 Design Methodology

Within the nuclear power plant, several functions and subfunctions are performed to ensure safe and efficient operation. Before identifying the functions, we first identified the high-level systems and/or equipment responsible for the processes described in Figure 2.1.

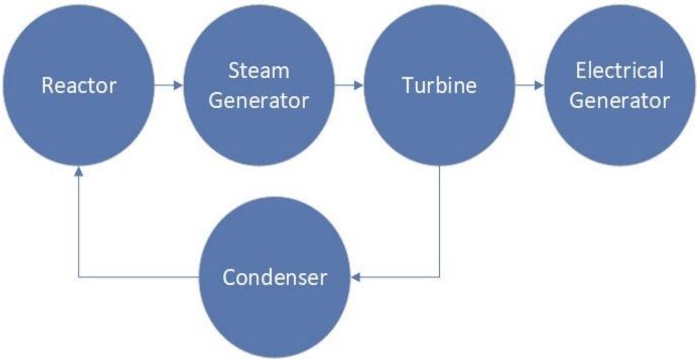


Figure 2.1 Identified systems/components

Maintaining safety and dependability for nuclear power applications depends on its contribution to containment, pressure and temperature control, radiation shielding, structural support, and system integrity.

A reactor vessel's main use is to contain radioactive elements produced during nuclear fission, serving as a barrier, preventing the release of radioactive materials in the surrounding environment, and guaranteeing public and worker safety [16].

Reactor vessels are made to resist high pressures and temperatures, therefore facilitating effective heat transfer and power generation. Their maintenance of ideal conditions for the coolant helps to enable the regulated release of thermal energy [17].

The analytical objective of the vessel is to lessen the radiation exposure of individuals working in the area by providing shelter through its robust shell while ensuring that the fission products are contained within the walls of the reactor, thus protecting anyone working nearby and the environment [18].

The reactor vessel provides structural support to important components within the core, such as the reactor core, control rods, coolant channels, and internal systems and that is why the design of the reactor vessel should be strong and durable enough to guarantee the reliability and steadiness of the systems it contains [19].

The vessel's design shall incorporate safety elements that can endure severe circumstances, such as possible accidents or failures. If a final version is agreed upon, the product shall be subjected to thorough testing to verify its capacity to confine and regulate nuclear reactions, hence preventing the emission of hazardous substances [20].

2.2 Design Optimization and Iterations

The CAD design process involved periodic modification of the models to align with additive manufacturing technology and to fulfil the needs presented in the previous subchapter.

The design methodology presents the iterative process of creating the desired model, establishing needs, and enhancing them to align with industry standards and the desired capabilities of the model.

The iterative approach involves the possibility of modifying the model, specifications, and needs as a result of feedback received throughout the process. The technique depicted in Figure 2.2 is derived from the Pahl and Beitz process for conceptual design and has been modified for the several phases that have been identified [21].

At its core, the Pahl and Beitz methodology emphasizes a systematic and iterative design process, involving various stages such as problem identification, concept generation, evaluation, and embodiment design. The sixth stage within the methodology is the most laborious and intensive one as it includes the types of analysis suitable for a reactor vessel and comparison with acceptance criteria identified in technical literature such as ASME Boiler & Pressure Vessel Code [22].

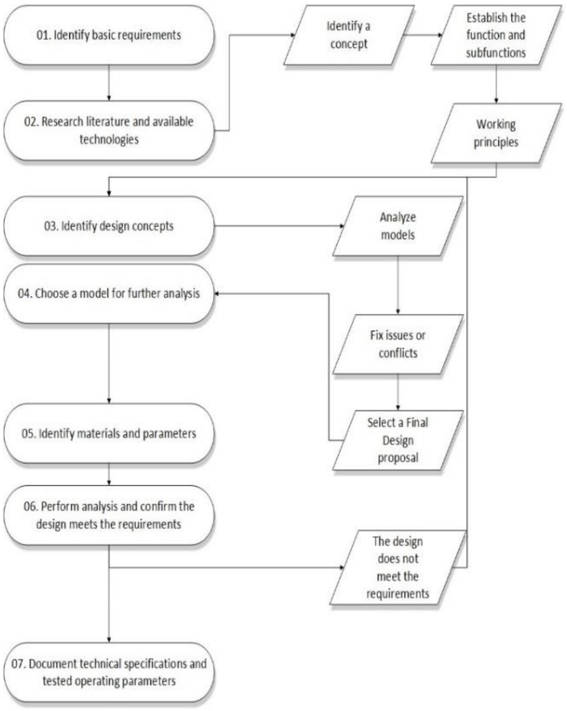


Figure 2.2 CAD Methodology

The choice of a cylindrical shape for the reactor containment vessel relies on technical concepts, operating experience of existing nuclear facilities and practical factors that enhance structural integrity, manufacturability, and operational efficiency. It reduces stress concentrations, allowing for better resistance to internal pressures and thermal stresses. The cylindrical shape also simplifies fabrication and use of additive manufacturing methods, reducing welding difficulties and minimizing failure chances. It facilitates effective heat dissipation, space efficiency, and integration with auxiliary systems. Cylindrical layers also facilitate radiation shielding installation, ensuring constant protection so that the design meets safety, performance, and manufacturability requirements for nuclear microreactors.

In addition, the nuclear microreactor containment vessel was embedded with heat pipes, this cooling method was chosen for its compatibility with the reactor's geometric and thermal management requirements, using the cylindrical shape of the vessel to function optimally when arranged in a radial configuration. This structure facilitates the even removal of heat to exterior heat exchangers, hence lowering temperature differences and minimising the possibility of localised areas of high temperature that could cause damage or failure of materials. Heat pipes, utilising passive capillary action and phase-change mechanisms, increase the overall efficiency of heat evacuation in the cylindrical design without the need for complex moving parts or additional energy input. This integration facilitates both safety and performance by facilitating the dissipation of heat during regular operation as well as in transient or emergency situations. the heat pipe arrays, benefiting from consistent contact and thermal coupling and increasing the reactor's ability to regulate its temperature. This design decision is presented in Figure 2.3, should help both the safety margins and the compact, scalable characteristics of microreactor systems.

The conceptual designs for the reactor vessel were developed using ANSYS SpaceClaim, a 3D CAD software, this software was chosen for its integration with other CFD software. Thermal simulation in ANSYS Fluent will be used to simulate heat transport within the vessel on the interior pipes that were built to improve heat exchange and prevent hot spots. Geometric constraints regarding height, width, and internal volume are implemented from the early-stage designs. The design iterations progressed, integrating multiple cooling systems, and incorporating circular shell piping.

The circular shell pipes are designed in subsequent iterations to guarantee a secure and effective cooling system, as illustrated in Figure 2.3. Upon the introduction of Figure 2.4 (scaled-down version 1:2), the design has undergone iteration and optimisation to incorporate a scaled prototype for additional testing, establishing a solid basis for thermal analysis.

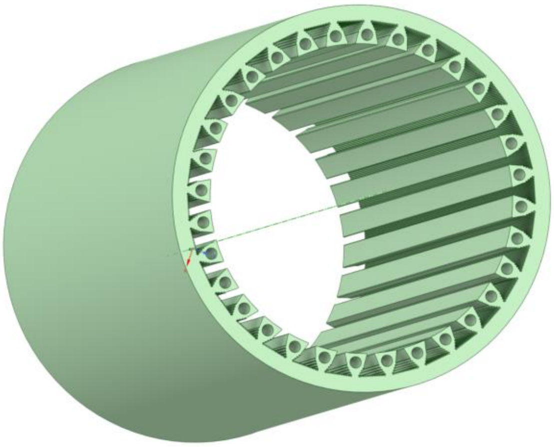


Figure 2.3 CAD Model - Initial design

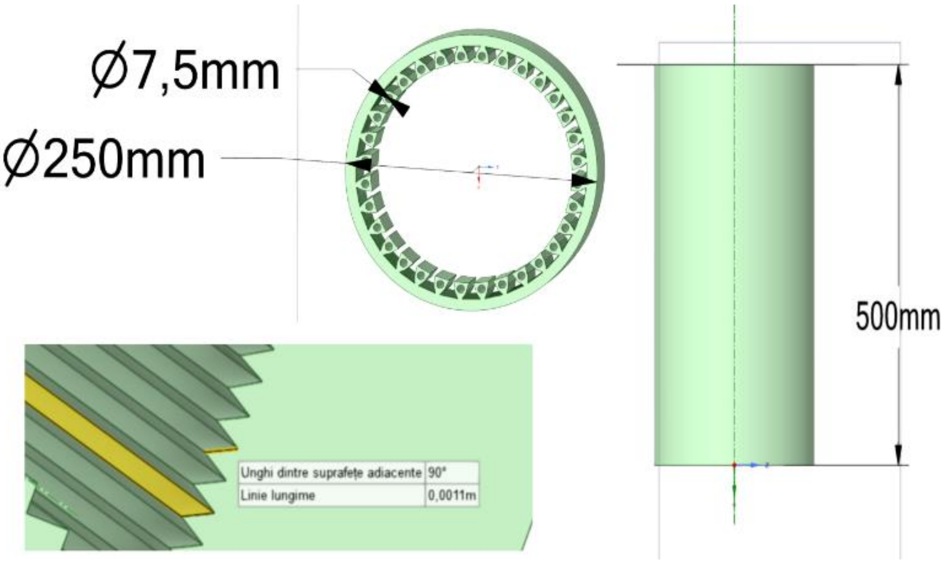


Figure 2.4 Initial design geometric considerations

The design maintains consistent proportions with the original, including features like the 125 mm dome and cylindrical body height of 247.21 mm. This scaled version allows for smaller-scale analysis and testing, ensuring that the primary design characteristics are retained while minimizing resource usage during the fabrication process. This particular iteration was made with the thought of manufacturing the whole model in one single part with the limitations of existing additive manufacturing printing platforms.

Table 2.1 Conceptual Design Models – specification comparison

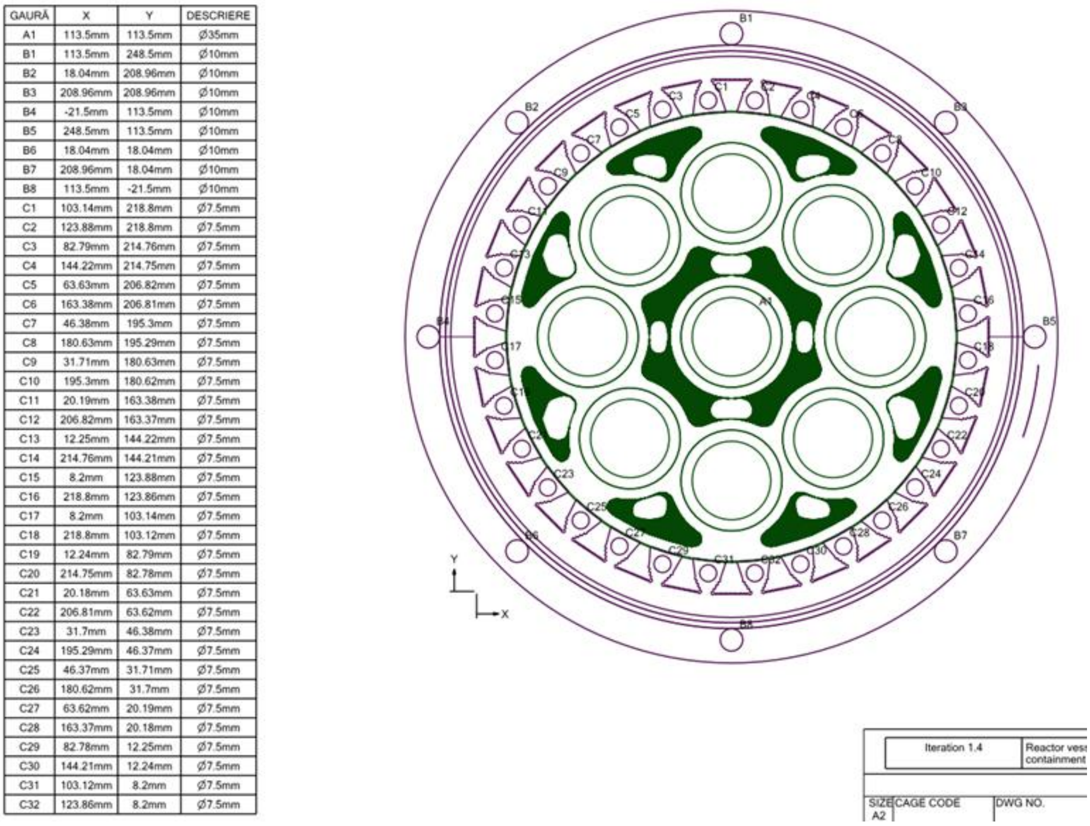
Parameter	CD 3	CD 2	CD 1	Final Design
Vessel Mass	48,2219 kg	45,3332 kg	76,9689 kg	125,1254 kg
Height	0,25m	0,25m	0,25m	0,25m
Width	0,25m	0,25m	0,25m (0,29 m – including pipes)	0,25m
Length	0,67m	0,67m	0,7839m	0,65734m
Vessel Interior Volume	0,0241m^3	0,0231m^3	0,0241m^3	0,016 m^3
Piping total volume	0,0011m^3	0,003m^3	0,0011m^3	ø7,5mm -0,0011m^3 ø35mm -0,0063 m^3 Total -0,0074 m^3
Vessel Material	Stainless Steel 316L	Stainless Steel 316L	Stainless Steel 316L	Stainless Steel 316L
Vessel Material Density	8000 kg/ m^3	8000 kg/ m^3	8000 kg/ m^3	8000 kg/ m^3
Working fluid	Water or Helium (Not defined yet)	Water or Helium (Not defined yet)	Water or Helium (Not defined yet)	Water or Helium (Not defined yet)
Estimated water mass within the volume	22,92 Kg	23,1342Kg	25,2203Kg	25,2203Kg
Estimated volume of fluid	0,0229 m2	0,0231 m2	0,0251 m2	0,0251 m2
Total fluid surface area	1,1833m2	1,3411m2	2,613 m2	2,613 m2

Estimated gas(helium) mass within the volume	0,0041 Kg	0,0041 Kg	0,0041 Kg	0,0041 Kg
Piping information	10 pipes with 10 inlets and 10 outlets arranged in a circular pattern.	5 pipes with 5 inlets and 5 outlets arranged in a circular pattern.	16 pipes with 16 inlets and 16 outlets arranged in a circular pattern.	ø7,5mm -16 pipes with 16 inlets and 16 outlets arranged in a circular pattern. ø35mm – 9 pipes that pass through the vessel
Pipe interior diameter	ø15mm	ø 15mm	ø 7,5mm	ø7,5mm ø35mm
Vessel maximum thickness	12,5 mm	12,5 mm	13,2856 mm	13,2856 mm
Vessel minimum thickness	5 mm	2.5 mm	2.17 mm	2.17 mm

Table 2.1 presents the design evolution of the models considered to be microreactor containment vessels through three initial concepts (CD1, CD2, CD3) which contribute to one final design. During the development phases, the vessel mass varies, beginning at 76.97 kg in CD1, decreasing to 45.33 kg in CD2, and then marginally rising to 48.22 kg in CD3. The final design, however, weighs 125.13 kg, attributable to additional features and structural enhancements imported from all three designs. The vessel's height (0.25m) and width (0.25m) are consistent, while the length exhibits minor variation, culminating in a final measurement of 0.657m, indicating a small degree of compactness compared to previous iterations. The final design presents a reduction in interior volume (0.016m^3), this is because of the optimisations intended to improve performance, minimise surplus material, increase flow through dedicated channels and increase overall stability through the mesh-like support of the piping.

The vessel is engineered to accommodate either water or helium as the working fluid, with no conclusive decision reached at this time. The fluid capacity is identified as 0.0251 m^2 in all designs, with varying piping configurations in the final design featuring a dual-pipe system for optimal fluid dynamics and thermal exchange and the identified piping volume is 0.0074 m^3, slightly increased from previous iterations. The thickness of vessels varies from 13.29 mm to 2.17 mm, balancing material strength and weight. The surface area that may be occupied by fluids increases in CD1 and remains unchanged in the final design. Several design changes in the final design, that were made to increase the overall physical stability of the model, may present better results both for physical resistance, fluid flow and thermal exchange.

Figure 1. 4 presents the location and dimensions of all of the identified hole's present in the final model. and Figure 1. 5 highlight the wireframe and section view of the model with overall dimensions.



GAURĂ	X	Y	DESCRIERE
A1	113.5mm	113.5mm	Ø35mm
B1	113.5mm	248.5mm	Ø10mm
B2	18.04mm	208.96mm	Ø10mm
B3	208.96mm	208.96mm	Ø10mm
B4	-21.5mm	113.5mm	Ø10mm
B5	248.5mm	113.5mm	Ø10mm
B6	18.04mm	18.04mm	Ø10mm
B7	208.96mm	18.04mm	Ø10mm
B8	113.5mm	-21.5mm	Ø10mm
C1	103.14mm	218.8mm	Ø7.5mm
C2	123.88mm	218.8mm	Ø7.5mm
C3	82.79mm	214.76mm	Ø7.5mm
C4	144.22mm	214.75mm	Ø7.5mm
C5	63.63mm	206.82mm	Ø7.5mm
C6	163.38mm	206.81mm	Ø7.5mm
C7	46.38mm	195.3mm	Ø7.5mm
C8	180.63mm	195.29mm	Ø7.5mm
C9	31.71mm	180.63mm	Ø7.5mm
C10	195.3mm	180.62mm	Ø7.5mm
C11	20.19mm	163.38mm	Ø7.5mm
C12	206.82mm	163.37mm	Ø7.5mm
C13	12.25mm	144.22mm	Ø7.5mm
C14	214.76mm	144.21mm	Ø7.5mm
C15	8.2mm	123.88mm	Ø7.5mm
C16	218.8mm	123.86mm	Ø7.5mm
C17	8.2mm	103.14mm	Ø7.5mm
C18	218.8mm	103.12mm	Ø7.5mm
C19	12.24mm	82.79mm	Ø7.5mm
C20	214.75mm	82.78mm	Ø7.5mm
C21	20.18mm	63.63mm	Ø7.5mm
C22	206.81mm	63.62mm	Ø7.5mm
C23	31.7mm	46.38mm	Ø7.5mm
C24	195.29mm	46.37mm	Ø7.5mm
C25	46.37mm	31.71mm	Ø7.5mm
C26	180.62mm	31.7mm	Ø7.5mm
C27	63.62mm	20.19mm	Ø7.5mm
C28	163.37mm	20.18mm	Ø7.5mm
C29	82.78mm	12.25mm	Ø7.5mm
C30	144.21mm	12.24mm	Ø7.5mm
C31	103.12mm	8.2mm	Ø7.5mm
C32	123.86mm	8.2mm	Ø7.5mm

Figure 1. 4 Location and size of identified holes in the final model

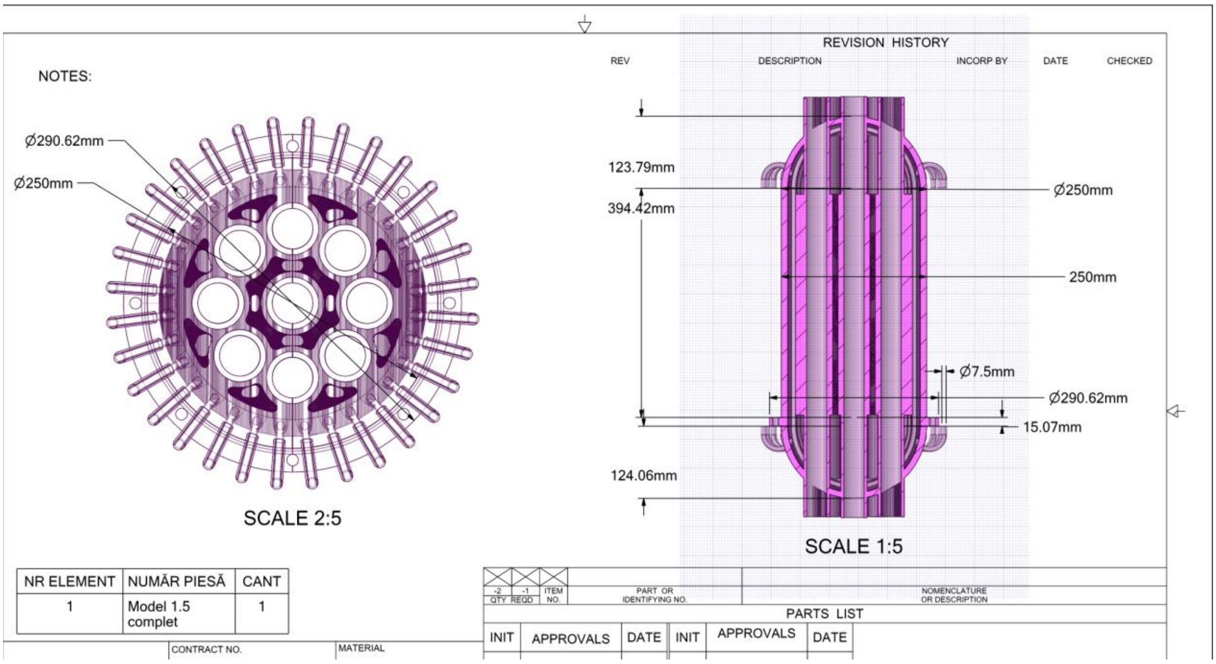


Figure 1. 5 Wireframe and section view of the final model

Chapter 3. Thermal Analysis of the Containment Vessel

3.1 Boundary Conditions and Assumptions

The initial assumptions of the analysis are:

- The temperature at the exterior pipe surface was selected for three different temperatures to verify which is optimum for evacuating an optimum amount of heat for the specific flow of each pipe. The selected temperatures are 500°C, 550°C and 600°C.
- To make better use of simulation capability we selected three pipe diameters that would fit in the vessel geometry and would provide sufficient flow to evacuate the required heat. The distribution of these within the geometry would take place after the results are presented. The pipe diameters selected are 10mm, 7mm and 5mm.
- We have taken into consideration gravity at 9.8 m/s2.
- Mesh configuration is slightly changed for each iteration due to changes in pipe diamete.
- Pipe thickness is maintained the same in all models at 2.5 mm.

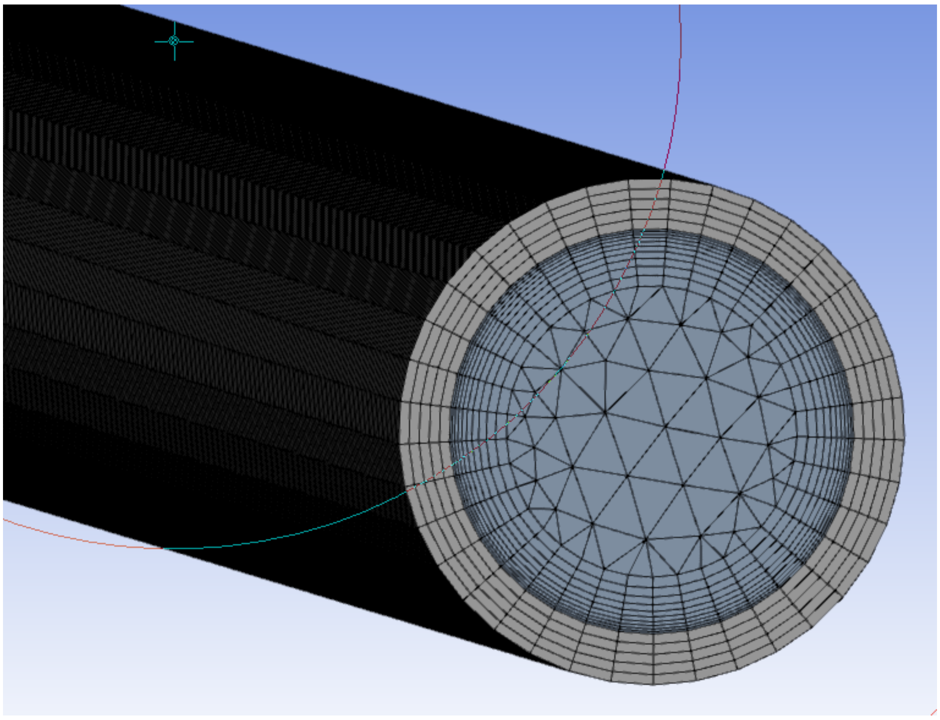


Figure 3.1 Mesh configuration used in the analysis

The mesh presented in Figure 3.1 was selected to provide a balance between capturing the boundary layer in detail, with more density for the hexahedral mesh, while the middle of the pipe has a triangular larger mesh, less structured to allow the available computing power to be focused where the process is worth monitoring.

This analysis monitors the behaviour of the selected material while transporting hot fluid and how it facilitates further heat transfer.

CFD modelling uses named selections to categorise bodies or surfaces to facilitate the setup of the analysis and post-processing to select relevant data. The named selection for this analysis is presented in Figure 3.2.

Named selections were made for the following surfaces/bodies:

- Inlet (fluid - surface)
- Outlet (fluid - surface)
- Fluid (fluid -body)
- Exterior pipe (solid - surface)
- Interior pipe (solid - surface)
- Inlet pipe (solid - surface)
- Outlet pipe (solid - surface)
- Wall Fluid (wall)

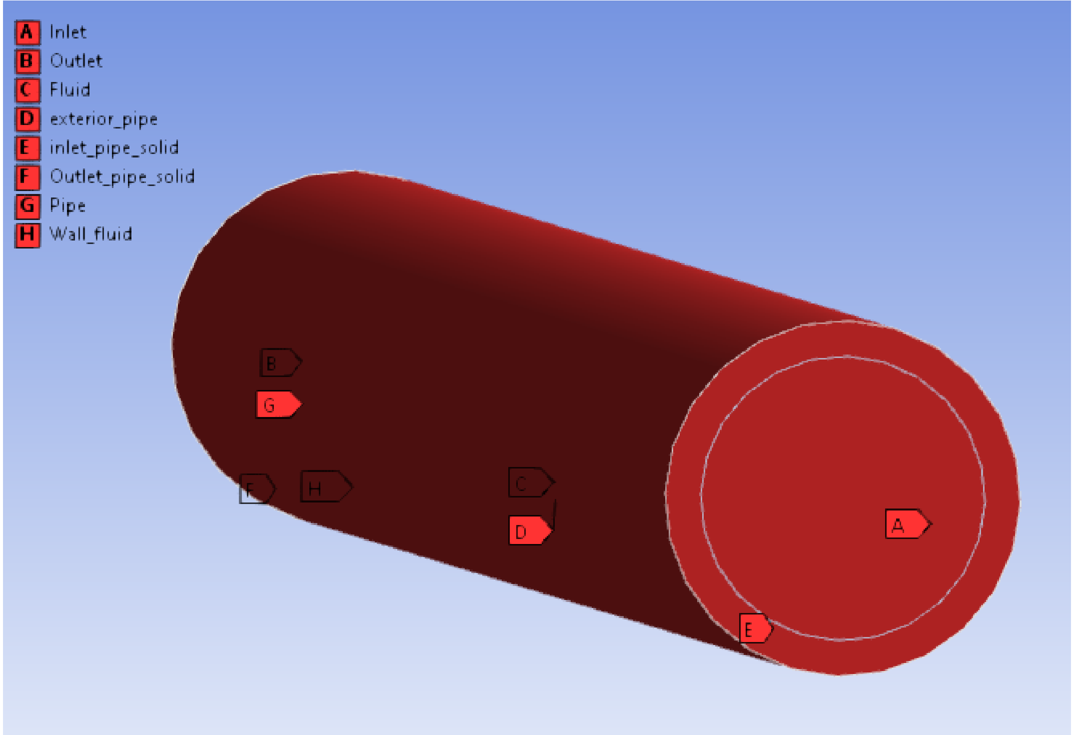


Figure 3.2 Named Selection for pipe models

The named selections remained the same for each analysis for continuity, to compare the results and to avoid errors in the process.

For material properties simulated in the analysis, the ANSYS material database from engineering data sources was used [23]. Selecting the material from the software database is beneficial because it contains documented measurements of changes in material properties when the temperature is changed. This software also has representative values for SS316L for additive manufacturing, this means that the results are representative.

Table 3. 1 SS316L density variation with temperature [64]

Temperature In Celsius	SS316L Density ($kg\times m^{-3}$)
26,85	7954
126,85	7910
226,85	7864
326,85	7818
426,85	7771
526,85	7723
626,85	7674
726,85	7624
826,85	7574
926,85	7523
1026,85	7471
1126,85	7419
1226,85	7365
1326,85	7311

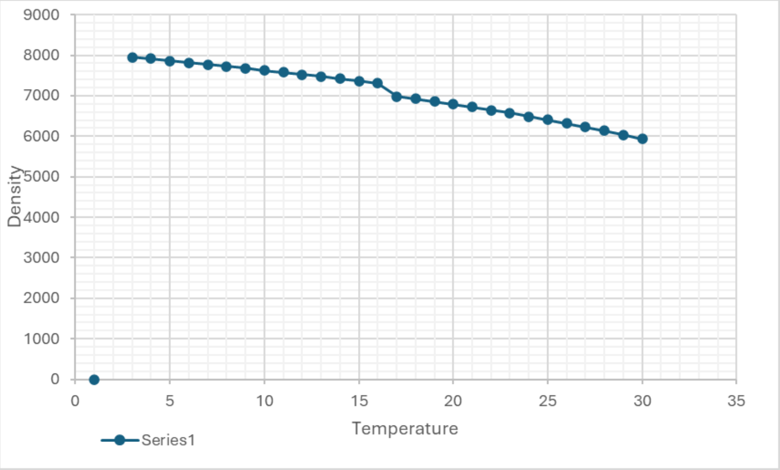


Figure 3.3 SS316L AM Density variation with temperature

Table 3. 1 presents the available database for the behaviour of SS316L and its variation with temperature is graphically represented in Figure 3.3. There the variation in density of SS316L with temperature can be observed, which indicates a trend of decreasing density as temperature increases. Starting from 7954 kg/m³ at approximately 27°C, the density steadily decreases, reaching 5930 kg/m³ at 2727°C. This trend represents the behaviour of SS316L AM as it expands with increasing temperature, leading to a reduction in density. Considering the operating temperature for this analysis no significant changes in material density are expected in the temperature interval between 27°C- 600°C whereas other scenarios that involve higher temperatures may require more processing power. In this model, it is assumed that the material density will remain constant.

The following boundary conditions were selected:

- Velocity Specification Method: Magnitude, Normal to boundary.
- Reference frame: Absolute.
- Velocity magnitude: 1.5 m/s.
- Turbulence intensity fraction: 0.05.
- Turbulence viscosity ratio: 10.
- Temperature at fluid inlet: 280°C.
- Gauge pressure at outlet: 50 bar.
- Backflow direction specification method: normal to the boundary.
- Backflow Turbulent Intensity Fraction: 0.05.
- Backflow Turbulent Viscosity Ratio: 10.
- Exterior pipe temperature values of 500°C, 550°C and 600°C.
- Inlet Pipe Solid: 300°C.
- Wall motion: Stationary Wall.
- Shear Condition: No Slip.
- Roughness Models: Standard.
- Thermal Conditions: Coupled.

3.2 Analysis and Interpretation

The analysis was performed on representative samples of the pipes, these samples shall provide thermal and velocity feedback from simulating a fluid travelling at a constant speed through the pipe and being heated from the outer shell of the pipe.

For each pipe model there is expected feedback from the analysis which covers the following:

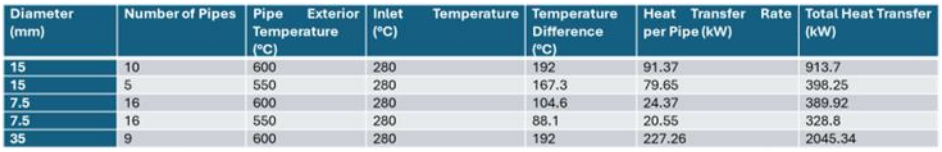
- Thermal behaviour and heat transfer.
- Velocity feedback.
- Thermal expansion and stress are discussed for this analysis as the diameter has been selected conservatively at 2.5mm. The pipes run through the containment vessel and shall have more thickness and support than those included in this simulation.

All pipes have a length of 500mm, it has been selected like this because of the total length of the containment vessel which is the same.

An uncertainty that needs to be considered for further analysis is the pipe distribution in the vessel and how it affects the heat transfer and velocity feedback. Flow may be influenced if all pipes are supplied from a single source of cooling agent.

3.3 Conclusions and Author Contributions

This part of the research presents a thermal analysis for different pipe diameters and configurations used within a containment vessel of a nuclear reactor to determine effective heat management.



Diameter (mm)	Number of Pipes	Pipe Exterior Temperature (°C)	Inlet Temperature (°C)	Temperature Difference (°C)	Heat Transfer Rate per Pipe (kW)	Total Heat Transfer (kW)
15	10	600	280	192	91.37	913.7
15	5	550	280	167.3	79.65	398.25
7.5	16	600	280	104.6	24.37	389.92
7.5	16	550	280	88.1	20.55	328.8
35	9	600	280	192	227.26	2045.34

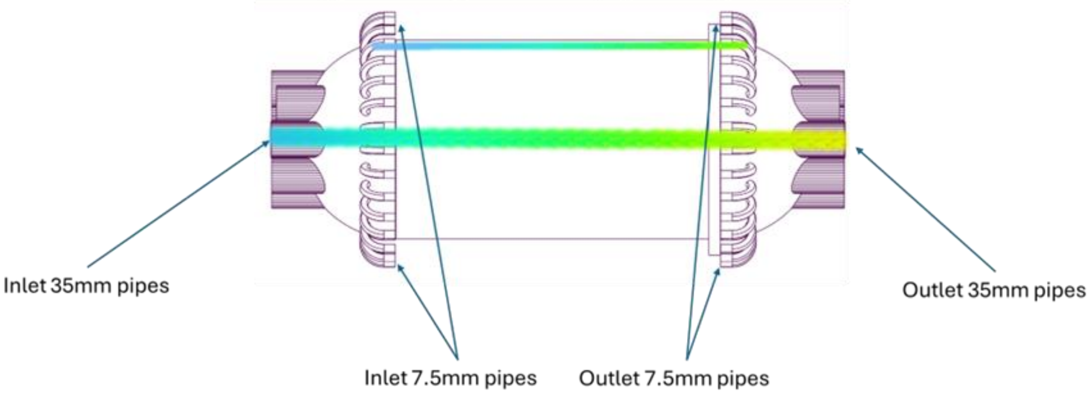


Figure 3.4 Heat exchange model

Based on the heat exchange model presented in Figure 3.4, several solutions emerge with only the one with 35 mm pipe section surpassing the target of 2Mw thermal power. Further study needs to refine the identified models and proceed with experimental validation.

The analysis draws the following conclusions:

- The simulation results show that larger pipe diameters, simulated in this analysis as 35 mm model pipes, are more effective in transferring heat, with a heat transfer rate of approximately 227.26 kW per pipe at 600 °C. This configuration meets the target for efficient thermal evacuation, suggesting it is suitable for primary heat transport from the reactor core.

- Smaller pipe diameters, such as 5 mm and 7 mm, demonstrated effective heat transfer; with significantly lower heat transfer rates, these smaller pipes could be suitable for supplementary cooling applications or may meet primary cooling requirements coupled with the larger diameter pipes.
- The fluid velocity profile remained the same across all pipe configurations and outside temperatures (500°C, 550°C, and 600°C). This shows that the flow regime within the pipes is mostly unaffected by changes in temperature at the thicknesses that were studied. This stability means that the coolant will flow reliably under a range of operational conditions.
- High thermal gradients, especially in the 35-mm-diameter pipes with high surface temperatures, are likely to introduce significant thermal stress within the pipe material. Future studies should examine this aspect further to ensure mechanical integrity and prevent material fatigue or failure over prolonged operation under similar conditions.
- The results of the analysis indicate the necessity for a balanced thermal management system that combines different pipe diameters, with larger pipes for primary heat evacuation and smaller pipes for supplemental cooling.
- Future studies should focus on thermal stress and material degradation due to prolonged exposure to high-temperature gradients and radiation; a more complex model involving multiple coolant sources could provide insights into optimizing cooling system configurations within the containment vessel.

The author contributed to:

- Design and set up the thermal simulation in ANSYS CFD.
- Ran the computational fluid dynamics (CFD) simulations across various temperature and pipe diameter configurations to study thermal behaviour and fluid dynamics.
- Analysed simulation outputs for temperature gradients, fluid velocity profiles, and heat transfer rates for each pipe diameter under different temperature conditions.
- Compiled results into tables and figures (e.g., temperature and velocity profiles for each configuration) and prepared volume renderings to visually represent simulation outcomes.
- Conducted preliminary comparisons, noted areas for further research, and assessed implications for reactor safety and efficiency.

The following articles were published from the work performed in this chapter:

1. Sumanariu, A., Oprisescu, M., & Amza, C. (2024). NUCLEAR MICRO-REACTOR THERMAL ANALYSIS METHODOLOGY. Nonconventional Technologies Review, 28(2)

Chapter 4. Testing of 3D Printed 316L Stainless Steel Samples

4.1 AM and Conventional Sample Comparison of results and discussion

In this part of the study, we will compare the mechanical behaviour under stress conditions of AM samples E series and conventional samples T series. Moving further, the research will address the test results after performing a uniaxial tensile test using a Forta Instron 8800 machine. The experimental setup measured the mechanical response of the samples under increasing load, this load was measured in a step sequence and analysed.

The following parameters were monitored:

1) The relative analogue input, which represents the applied load for each sample at each specific step, is captured as a relative analogue input, and it increases as the test progresses.
2) The mean effective strain (Von Mises strain) is monitored and recorded for each step, overall, it measures the mean effective strain over the surface area of the sample. This parameter is useful in assessing material ductility and is measured in percentages.
3) Two mean principal strains are monitored, the first represents the strain over the surface showing the maximum strain in one direction and the second represents the minimum strain in the perpendicular direction.
4) Sigma is a calculated value that represents the stress value at each step, corresponding to the force per unit area on the sample.

For each sample, the test starts from a baseline with zero applied load and as the load increases it is expected that strain values will also increase in both directions along with sigma values representing the material's deformation response to the applied load. The strain.

The two sample series T and E are analysed and discussed moving further for each sample test and the observed parameters are documented summarising the data from both sample series.

4.2 Conclusions and Author Contributions

The stress-strain curves and SEM pictures of the fractured samples made with AM demonstrate better tensile and yield strengths than samples made with conventional methods, with more fine grain structure seen in the SEM images that is indicative of the usual traits of AM processes. They are also slightly less ductile, as shown by their lower elongation at break values, despite increasing strength, the distribution of the grain structure indicates that the additive manufacturing process may impair ductility. SEM examination of AM samples indicated that the material's decreased flexibility before failure may be attributed to voids, and microstructure abnormalities. Despite having less tensile strength, samples made using traditional production methods demonstrated greater flexibility.

The statistical technique known as ANOVA, or Analysis of Variance, determines whether there is a documented difference between the average values of three or more monitored values in this particular case, assessing the impact factors and their statistical significance for the research [24].

After grouping the collected data, the F-value (the ratio between two variances) and probability values were determined. Significant variations in tensile characteristics across the groups are indicated by a probability value less than 0.05, which suggests that these variations were caused by the particular circumstances of the samples such as material flaws, environmental factors rather than being random.

The findings of the samples' tensile stress tests, which are shown in Table 4.1and are depicted in Figure 4.1, were subjected to an analysis of variance. In the previously shown sample series, the tensile stress at the point of maximal strength and the tensile stress at the point of yield were compared. The numbered AM series and the T conventional series had the highest F-statistic, and we found differences in the yield strengths across all sample comparisons. At the point of tensile strength, the tensile stress fluctuates, and the p-values are frequently greater than the yield stress p-values.

Table 4.1 Sample Analysis Using ANOVA

Comparison Groups	Mechanical Property	F-value	Probability Value
S1-S5, 1-5, E1-E5, T1-T5	Yield Tensile Stress	57.61	$8.53 \cdot 10^{-9}$
S1-S5, 1-5, E1-E5, T1-T5	Tensile Strength	13.60	$1.15 \cdot 10^{-4}$
S1-S5 and T1-T5	Yield Tensile Stress	76.50	$2.28 \cdot 10^{-5}$
S1-S5 and T1-T5	Tensile Strength	9.27	0.016
1-5 and T1-T5	Yield Tensile Stress	559.58	$1.08 \cdot 10^{-8}$
1-5 and T1-T5	Tensile Strength	92.58	$1.13 \cdot 10^{-5}$
E1-E5 and T1-T5	Yield Tensile Stress	87.40	$1.40 \cdot 10^{-5}$
E1-E5 and T1-T5	Tensile Strength	-	-

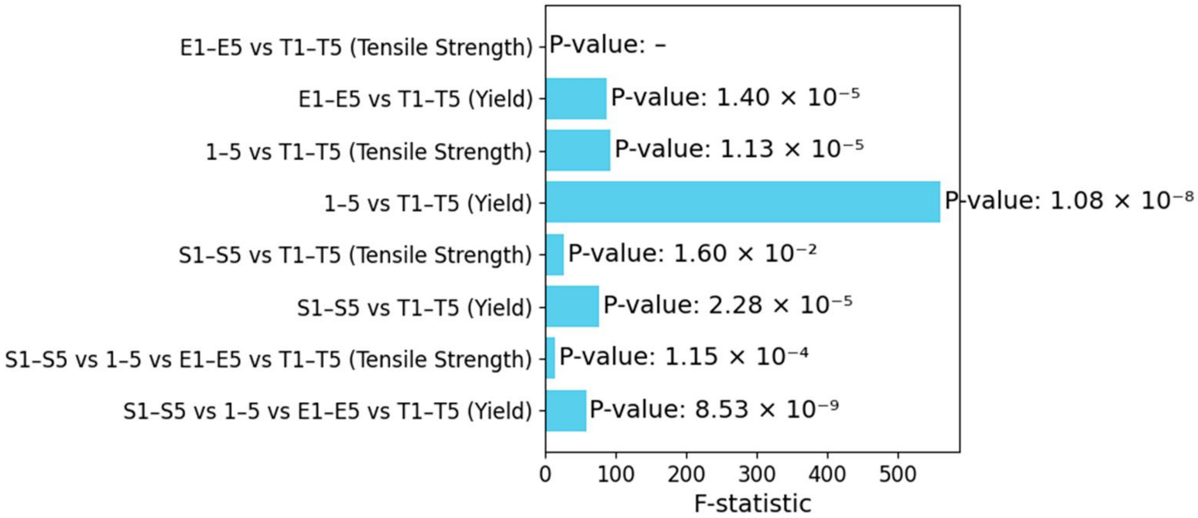


Figure 4.1 F-Statistic Comparison Across Different Sample Groups

The compromises related to the production processes were established by a comparison of SS316L samples made using additive and conventional methods. Additive manufacturing increases the tensile and yield strength of materials by producing a more refined microstructure, but with a slightly decreased ductility of approximately 10% compared with the conventional samples. Customizing the manufacturing processes to the specific needs of the application is required when choosing the right production method. For certain applications, AM's increased strength is advantageous, whereas conventional production techniques might work better for applications that call for a balance between strength and flexibility.
AM's relatively quick cooling and solidification processes produce a smaller grain structure and a higher dislocation density, which influence tensile strength.
The relatively rapid cooling and solidification rates in AM provide finer grain structure and greater dislocation density, therefore affecting the tensile strength.

Conventionally manufactured stainless steel 316L has a microstructure with bigger grains that are more uniformly distributed. The microstructure of AM SS 316L, on the other hand, has finer grains and columnar grain development orientated in the build direction due to the rapid cooling of the AM process. The AM samples have more porosity and anisotropy than components made conventionally, which affects mechanical parameters like tensile strength and ductility. Grain refinement in AM samples increases strength but decreases ductility. [25], [26].

Compared to conventional approaches, the SLM AM process improves the microstructure by defining the finer grain architecture through its quick cooling and solidification speeds. Additionally, the material characteristics are enhanced by the layer-by-layer construction that produces sharp temperature gradients and encourages columnar grain formation in the build direction [26].

The material becomes more brittle when microstructural flaws like porosity, anisotropy, and residual stresses are present because they diminish the material's capacity for plastic deformation. Rapid solidification produces fine grain structures that boost strength but also reduce ductility by limiting the material's ability to elongate before failing.

Larger grain sizes in conventionally produced stainless steel 316L allow for more dislocation movement and plastic deformation, which improves ductility. Larger grains weaken grain boundaries, which can help explain the increased ductility seen. As a result, the material can stretch and absorb more strain before breaking. Particular restrictions must be noted when evaluating the findings and conclusions.

The research only used shot peening to post-process the samples it presented; it did not particularly focus on other post-processing techniques.

As additive manufacturing technology advances, there is a significant likelihood that the nuclear sector will increasingly utilize AM parts and/or materials for more critical components. This would streamline the process of fabricating specific components on-site and qualifying them for the intended environment.

Similar behaviour of AM SS316L material qualities was noted by D'Andrea, who showed in their work that the hardness of the material may be significantly affected by post-processing processes. Furthermore, the specimens' fatigue characteristics are influenced by the construction direction and austenite stability [17].

When comparing two specimens, Kedizora et al. additionally noticed that the SS316L material produced using the EOS machine models employing the SLM process models had the maximum fatigue strength. Additionally, they discovered that heat treatment does not always increase a material's flexibility [27]. During the melt pool development, Jeyaprakash concentrated on the process factors and their effects on the microstructural orientation of SS316L [28]. To find the best post-processing procedure for increasing ductility while lowering the compromise of other qualities, more research into these findings is required.

Future research should concentrate on determining the ideal equilibrium among energy density, laser power, velocity, layer thickness, and cooling rates. Phase analysis and microstructural characterisation should be employed to confirm the best selection of process parameters. [27], [28].

Dash A. et al. [29] state that the fabrication of radial bimetallic frameworks offers unique prospects for the design and production of components with enhanced mechanical properties.to

As found in relevant literature the hot isostatic pressing (HIP) post-processing procedure diminishes internal porosity, enhances material density, and also implies a specific heat treatment, which reduces residual stresses. Similar procedures like shot peening, surface laser melting and ultrasonic nanocrystalline surface modification can address surface modification, stress concentrations, and improve mechanical properties of the samples [30] [31].

Particular application criteria that may influence the choice between additive manufacturing and conventional manufacturing methods for SS316L have been discussed and the choice between additive manufacturing (AM) and traditional production for SS 316L is contingent upon the factors the designer is prepared to address for specialized applications like medical implants, aerospace, or nuclear technologies.

To summarise, additive manufacturing is an appropriate production technique in the nuclear sector, industry, and SS316L is a suitable material. The discrepancies in sample outcomes reflect the diversity in sizes and forms of the samples and demonstrate enhancement relative to traditional samples. Further study is necessary to establish a uniform test strategy for these materials and technologies in the nuclear domain.

The conclusions from Chapter 4 data are:

- The use of selective laser melting (SLM) for SS316L creates materials with suitable mechanical properties that compared to the same alloy manufactured through conventional methods and is a good material for the purpose of this thesis which is to demonstrate that a microreactor using AM SS316L can operate safely. More detailed analysis must investigate the safety limits of operation and potential failure modes of the material.
- While it has been observed that the AM samples present enhanced strength, they also present reduced ductility. The refined grain structure and residual stresses from rapid cooling in the AM process contribute to this reduced flexibility, as indicated by lower elongation at break values.

- SEM analysis shows finer, columnar grains in AM samples aligned with the build direction, promoting higher strength but lower ductility. Conventional samples displayed larger, more evenly distributed grains that facilitate better plastic deformation.
- AM samples displayed higher tensile stress at yield and ultimate tensile strength compared to conventionally manufactured samples. However, the AM samples presented decreased ductility, due to porosity and anisotropy.
- Porosity and residual stress in AM samples contribute to void formation, which reduces flexibility. This indicates a need for optimized process parameters and potential post-processing treatments to improve AM sample properties.
- Voids, empty spaces, and microstructural irregularities observed in fractured AM samples indicate areas for process improvement. Reducing porosity through techniques like hot isostatic pressing could enhance material properties
- The statistical analysis confirmed significant differences in tensile properties between AM and conventional samples, reinforcing that manufacturing method influences mechanical behavior significantly
- AM samples maintained structural integrity post-irradiation, showing promise for nuclear applications. Initial testing suggests AM samples may withstand irradiation better than conventionally manufactured samples, but further testing is required after radiation doses decrease and permit proper manipulation.
- Further studies should focus on optimizing AM parameters like energy density, cooling rates, and post manufacturing heat treatment to enhance the balance of strength and ductility in AM SS316L. Additional research into post-processing methods such as heat treatment and stress relief will be necessary for broader industrial applications.

The author's contributions to this chapter are:

- Conceived and designed the study, including the selection of SS316L as the material and SLM as the primary additive manufacturing technique.
- Interpreted SEM data, assisting in identifying microstructural anomalies and potential process improvements for AM SS316L
- Analysed stress-strain data and performed ANOVA statistical analysis to evaluate differences in mechanical properties between AM and conventional samples.
- Conducted post-irradiation analysis, assessing the mechanical integrity and stability of samples exposed to neutron flux.
- Compiled the data, drafted the articles, and provided insights into the implications of AM for nuclear applications.

The following articles were published from the work performed in this chapter:

1. Sumanariu Constantin, Amza Catalin Gheorghe, Florin Baciu,Vasile Mihai, Nicoară Adrian. (2024). Comparative Analysis of Mechanical Properties: Conventional vs. Additive Manufacturing for Stainless Steel 316L. Materials. 17. 4808. 10.3390/ma17194808.
2. Sumanariu, C. A., Amza, C. G., Giolu, C., Stanciu, S., & Savu, M. (2024). SEM analysis of additively manufactured stainless steel 316L and conventional samples. Nonconventional Technologies Review, Romanian Association of Nonconventional Technologies, October 2024.

Chapter 5. Research Results and Conclusion

5.1 Research Results and Comparison with initial hypothesis

The nuclear sector faces both opportunities and challenges with the implementation of AM technology. Although AM may provide material efficiency and precision in nuclear microreactors, its properties and behaviour in nuclear-specific environments necessitate a strong regulatory framework.

The thesis hypothesizes that it is feasible to design a 2MW electric output microreactor containment vessel using additive manufacturing techniques, overcoming the limitations of traditional manufacturing methods, regarding the complexity, size constraints, and efficiency requirements of microreactor designs. The hypothesis is that AM can enable the production of a compact, efficient containment vessel capable of withstanding operational and thermal stresses.

The metrics resulted from the research are:

1. **Structural Metrics**

- **Vessel Mass**: (Ranged across designs with the final design at 125.13 kg).
- **Dimensions**:
  - **Height**: 0.25 m (consistently across designs).
  - **Width**: 0.25 m.
  - **Length**: Final design slightly compacted to 0.657 m.
- **Thickness**:
  - Max: 13.29 mm.
  - Min: 2.17 mm.

2. **Material Metrics**

- **Material**: Stainless Steel 316L.
- **Density**: 8000 kg/m³.
- **Thermal Properties**:
  - **Thermal Conductivity** (20°C): 16.2 W/m·K.
  - **Specific Heat Capacity** (20°C): 500 J/kg·K.

3. **Fluid Metrics**

- **Working Fluid Options**: Water was selected for the thermal analysis, but Helium provides a viable alternative.
- **Fluid Capacity**: 0.0251 m².
- **Estimated Water Mass**: Approx. 25.22 kg.
- **Total Fluid Surface Area**: 2.613 m².
- **Gas Mass (Helium)**: 0.0041 kg (approx.).

4. **Pipe Configuration Metrics**

- **Piping System**:
  - **CD1**: 10 pipes with 10 inlets and outlets (circular pattern).
  - **CD2**: 5 pipes (larger diameters, circular shell piping).
  - **CD3 (Final Design)**: Combination of 16 pipes with 7.5 mm diameter for flow and 9 larger 35 mm diameter pipes.
- **Pipe Interior Diameter**:
  - 7.5 mm for standard pipes.
  - 35 mm for larger flow channels in final design.

5. **Thermal Metrics and Requirements**

- **Temperature Resistance**:

  - **Max Operating Temperature**: 600°C to 800°C, designed to accommodate nuclear reactor conditions.
- **Pressure Ratings**:
  - **Water**: Up to 150 bar (1,450 psi).
  - **Helium**: Up to 150 bar (2,175 psi).
- **Leak-Tightness**: Target leak rate < 1.0 × 10^{-12} mbar·l/s.
- **Heat Exchange Surface**: Targeted > 2 m^2 for efficient thermal dissipation.

6. Heat Transfer Rates per Pipe

- **10 mm Diameter Pipes**:
  - At 600°C: 91.37 kW
  - At 550°C: 79.65 kW
  - At 500°C: 64.78 kW
- **7 mm Diameter Pipes**:
  - At 600°C: 24.37 kW
  - At 550°C: 20.55 kW
  - At 500°C: 16.76 kW
- **5 mm Diameter Pipes**:
  - At 600°C: 21.58 kW
  - At 550°C: 18.36 kW
  - At 500°C: 15.03 kW
- **35 mm Diameter Pipes**:
  - At 600°C: 227.26 kW

7. Total Heat Transfer Estimates

- **10 mm Pipes (10 units)**: ~913.7 kW at 600°C
- **7.5 mm Pipes (16 units)**: ~389.92 kW at 600°C
- **35 mm Pipes (9 units)**: ~2045.34 kW at 600°C
- Combined configuration meets target thermal evacuation requirements for effective heat dissipation.

8. Temperature Profiles and Fluid Velocity Observations

- **Fluid Velocity**:
  - Consistent velocity profiles were maintained across all pipe diameters and temperatures.
  - Average velocity at pipe center: ~1.5 to 1.98 m/s.
- **Thermal Gradients**:
  - Higher temperature differences were observed in larger pipes, indicating effective heat transfer but potentially increased thermal stress.
- **Temperature Drop Across Pipes**:
  - 10 mm pipes: ~192°C at 600°C
  - 7 mm pipes: ~104.6°C at 600°C
  - 5 mm pipes: ~181.7°C at 600°C

9. Stability and Flow Regime

- Stable laminar flow was maintained under all temperature conditions, with no significant turbulence.
- The stability in fluid velocity indicates dependable coolant flow across the pipes regardless of pipe diameter and temperature variance.

10. Design Implications

- **Optimal Configuration**: A mix of larger (35 mm) and smaller diameter pipes is recommended, with larger pipes focusing on primary heat evacuation and smaller ones for supplementary cooling.
- **Thermal Stress**: Larger pipes are more efficient in heat transfer but require further investigation into thermal stress impacts for long-term structural integrity.

11. Mechanical Integrity under Reactor Conditions

- **Ultimate Tensile Strength (UTS)**:
  - AM SS316L reached a UTS of 650–852 MPa, demonstrating its capability to withstand significant mechanical loads without catastrophic failure.
  - This high strength allows it to sustain structural integrity against potential internal pressures in microreactor containment.
- **Yield Strength**:
  - With an average yield strength of 565 MPa, AM SS316L exhibited robustness under prolonged mechanical stress, especially beneficial for core containment that undergoes stress cycles.
- **Ductility vs. Strength**
  - AM SS316L showed reduced ductility, with elongation at break around 40%, necessitating careful consideration of its flexibility in situations where thermal expansion and stress relaxation may be critical.

12. Radiation Tolerance and Structural Stability

- **Radiation-Induced Microstructural Changes**:
  - Post-irradiation SEM analysis confirmed minor radiation-induced surface restructuring in AM samples but no substantial mechanical degradation.
  - Void formation in AM samples did not worsen after irradiation, indicating a stable microstructure under neutron flux exposure.
- **Neutron Fluence and Irradiation Flux**:
  - Exposure to a neutron flux of $\sim 1.66 \times 10^{14}$ n/cm²/s over 25 days suggests resilience in the AM SS316L under reactor conditions.
  - The samples maintained structural integrity with estimated displacement per atom (DPA) around 0.3 (arc-DPA method), indicating limited susceptibility to radiation-induced dislocation.

13. Stress-Strain Response and Plastic Deformation

- **Elastic Modulus Consistency**:
  - AM SS316L exhibited an elastic modulus of approximately 185,000 MPa, which is slightly lower than conventional SS316L but within acceptable range for structural applications in microreactor design.
  - This modulus allows for predictable stress-strain response under operational loads, supporting the material’s role in reactor environments.
- **Strain Localization and Deformation Limits**:
  - High-strain localization areas appeared only at loads nearing yield strength, making the material suitable for sustained mechanical loads below these limits.
  - Progressive strain analysis showed that the material could transition from elastic to plastic deformation predictably, aiding in mechanical integrity assessments for containment designs.

14. Microstructural and Fracture Characteristics

- **Porosity and Void Dimensions**:

  - Voids in AM samples ranged from 300 to 600 nm in fractured sections, but structural stability persisted under operational and irradiation conditions.
  - The presence of fine grain structures with controlled porosity aids fracture toughness, with AM SS316L demonstrating ductile fracture characteristics that can absorb strain energy before fracture.
- **Microreactor-Specific Toughness**:
  - Fracture surface analyses suggest that AM SS316L can absorb stress due to its inherent microstructural voids, providing a controlled mechanism for energy dissipation under strain.
  - This toughness profile aligns well with requirements for microreactors, where resilience to both tensile and irradiation-induced stress is crucial.

15. Future Research Directions for Enhanced Microreactor Applications

- **Optimization of Process Parameters**:
  - Further refinement of laser power, energy density, and cooling rates in the AM process can help improve ductility and reduce microstructural anisotropy.
- **Post-Manufacturing Treatments**:
  - Post-processing techniques such as hot isostatic pressing or heat treatment could improve SS316L's mechanical robustness and minimize porosity.
  - Surface hardening and nitriding may also enhance the material's corrosion resistance and reduce oxidation, supporting long-term stability in reactor environments.
- **Comprehensive Irradiation Studies**:
  - Extended irradiation testing under varying neutron flux conditions could offer insights into SS316L's behaviour across different reactor operational stages.
  - Further studies on phase analysis and defect stability post-irradiation will help validate AM SS316L's durability and fracture resistance in actual reactor cores.

5.2 Contributions to the Field

The author made the following contributions to the research field:

Conceptualized and designed a microreactor containment vessel capable of generating 2MW of electric power, optimizing the design for additive manufacturing of SS316L.

Compiled insights from the latest literature on additive manufacturing applications in nuclear engineering, particularly emphasizing the unique benefits and challenges of AM in reactor design.

Identified and suggested solutions to issues including compact reactor dimensions, enhanced heat management, and refined material selection for microreactor systems.

Designed and analysed CAD models with integrated thermal management features, using heat pipes and other elements to enhance cooling efficiency under high-radiation and high-temperature conditions.

Identified and justified the selection of stainless steel 316L for the reactor containment vessel, emphasizing its compatibility with AM techniques and conducting testing for thermal and mechanical performance.

Addressed regulatory requirements for microreactors, including Romanian and European standards, and proposed measures to ensure safety, reliability, and compliance for AM-produced nuclear components

Investigated the technical and economic feasibility of AM for the containment vessel, analysing factors such as design freedom, manufacturing efficiency, and potential cost benefits over traditional methods.

Proposed methodologies and testing frameworks that can inform future AM applications in the nuclear sector, setting a foundation for continued research and development in microreactor technology.

Emphasized the need for further studies on irradiation, and post-irradiation mechanical stability in AM-fabricated components.

Proposed collaborations between industry and regulatory bodies to create guidelines and standards for AM in nuclear microreactors, supporting safe and innovative applications.

5.3 Limitations of the Study

The limitations of the research as identified in the thesis include:

The results and conclusions are specific to the selected manufacturing process (Selective Laser Melting - SLM) and material (SS316L), limiting the generalizability of findings across other materials and additive manufacturing processes.

Porosity levels vary depending on the machine type and model, as well as the materials used which may influence the mechanical properties and overall performance of the produced components, leading to potential inconsistencies across samples.

Only shot peening was utilized for post-processing in this study, while other techniques, like hot isostatic pressing, were not explored. This limits the understanding of how different post-processing methods might improve the material's ductility and structural properties.

The study encountered challenges with residual stresses and microstructural defects, including porosity and anisotropy, inherent to the SLM process. These defects contribute to reduced ductility and can limit the material’s suitability for applications requiring significant plastic deformation.

While initial visual analysis indicates the material's resilience to irradiation, more comprehensive, long-term studies are required to fully understand the behavior of AM-produced SS316L under sustained reactor conditions.

A significant limitation is the absence of specific standards for certifying AM materials for nuclear use. This gap presents regulatory and safety challenges, as current standards do not adequately cover the unique defects (e.g., porosity, residual stress) introduced by AM.

The study's thermal simulations utilized simplified pipe geometries and boundary conditions to reduce computational load. These simplifications may not fully capture the complex geometry and heat transfer dynamics present in an actual microreactor, such as varying surface areas and more intricate thermal gradients. The analysis was conducted over a specific range of external temperatures (500°C, 550°C, and 600°C) and with limited operational scenarios. Real-world microreactor conditions could involve broader temperature ranges, more extreme thermal flux, and variable power conditions that might alter the observed thermal behavior.

While the thermal analysis included SS316L properties from the ANSYS database, these properties may not fully represent additively manufactured (AM) SS316L, especially under high temperature, Variations in thermal conductivity, specific heat, and thermal expansion due to AM-induced microstructures could affect heat transfer accuracy, especially at elevated temperatures and should be validated in an experimental setup.

The coolant flow in the thermal analysis was kept constant, with limited exploration of transient or turbulent flow conditions. In real microreactor environments, the coolant flow could vary, introducing unsteady-state heat transfer and complex flow dynamics that might impact overall heat dissipation.

While temperature gradients were identified, the study did not extensively evaluate thermal stresses arising from these gradients.

The limitations in computational power led to a focus on specific diameters and baseline scenarios, restricting the ability to simulate full-scale reactor geometries or to explore a wider range of heat exchanger configurations.

5.4 Conclusions and future research activities

This research has presented a detailed process involving the design, material selection, thermal and mechanical characterization of a microreactor containment vessel, utilizing additively manufactured stainless steel 316L as the only construction material. Through testing and analysis, insights were derived regarding the performance, limitations, and potential improvements for AM SS316L within a nuclear microreactor environment. The following conclusions highlight the findings across structural, thermal, mechanical, and irradiation dimensions.

The containment vessel was designed to be compact and robust, with a final mass of 125.13 kg, dimensions of 0.25 m in height and width, and a length reduced to 0.657 m. These specifications balance structural stability with the operational space required for efficient reactor performance.

Wall thickness varied between 2.17 mm and 13.29 mm, ensuring reliable heat transfer metrics under various temperature reactor conditions.

The designed fluid system handled the heat transfer effectively, using water as the primary coolant, it provided sufficient thermal capacity.

AM SS316L showed a high ultimate tensile strength (UTS) between 650–852 MPa and an average yield strength of 565 MPa, indicating it can withstand considerable mechanical loads without failure

The material’s ductility, with elongation at break around 40%, suggests it is suited to containment structures where significant but controlled flexibility is required. However, the inherent reduced ductility of AM SS316L, compared to conventionally manufactured SS316L, warrants careful consideration for areas prone to thermal expansion.

Exposure of AM SS316L samples to a neutron flux of approximately 1.66×10^{14}n/cm^2/s over a 25-day period demonstrated visible resilience to radiation-induced microstructural changes, but due to increased radiation fields emitted by the materials activation limited the scope of the post irradiation analysis to visual inspection. Future analysis of the irradiated samples would provide valuable data for the behaviour of AM materials in high irradiation fields.

The samples maintained structural integrity with an estimated displacement per atom (DPA) of approximately 0.3 (using the arc-DPA method), indicating the material’s potential stability under reactor-like conditions.

While this study provides a decent foundation, several areas require further investigation to enhance the applicability of AM SS316L and optimize containment vessel designs for microreactors:

Future studies should focus on refining AM process parameters such as laser power, energy density, and layer thickness to enhance ductility and reduce anisotropy in AM SS316L.

Cooling rates and the effects of rapid solidification need in-depth investigation to fine-tune grain structures, aiming for an ideal balance between strength and flexibility.

Post-manufacturing treatments, including hot isostatic pressing (HIP) and heat treatment, could be explored to minimize residual porosity, improve ductility, and reduce internal stresses within the AM SS316L material.

Surface hardening techniques, such as nitriding, should be investigated to improve the corrosion resistance of the material, ensuring long-term durability under both high-temperature and irradiated conditions.

Irradiation of material for a longer period would bring more real-life data for analysis but would require even more time to allow researchers to analyse the samples.

Advanced analysis of phase changes, defect evolution, and microstructural stability post-irradiation will help to validate SS316L's resilience, particularly under prolonged neutron bombardment.

The corelation between thermal stress, neutron flux, temperature and pressure should be conducted to better understand the impact of high temperature and pressure on the vessel's structural stability over time.

Fatigue testing of AM SS316L, focusing on cyclic thermal loading and stress relaxation, would provide a more accurate depiction of the material's long-term performance, crucial for safe and sustainable reactor operation.

Exploring potential turbulence-promoting elements within the pipe design, could further enhance heat transfer efficiency while minimizing flow resistance.

Helium's use as a secondary or alternative coolant should be analysed in greater detail, examining its thermal and flow properties to determine the optimal fluid for specific reactor conditions.

The development of a standardized database capturing mechanical, thermal, and irradiation-related properties of AM SS316L will support the broader adoption of this material in microreactor designs.

A repository of AM parameters, post-treatment effects, and performance data will provide valuable resources for future designs, accelerating the development of next-generation nuclear containment materials.

This research has established the framework for the utilization of AM SS316L in microreactor containment vessel systems and offers the nuclear microreactor a new design that emphasises compactness, durability, and thermal distribution. Enhanced production methods and extensive study across various operational settings may enable AM SS316L to emerge as a predominant material in the developing compact nuclear reactor technologies. Future endeavours will expand the application of additive technology in the construction of effective and lasting reactor containment structures, thereby enhancing the safety, efficiency, and sustainability of nuclear energy systems.

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