NUCLEAR MICRO-REACTOR THERMAL ANALYSIS METHODOLOGY

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ABSTRACT: This paper presents a methodology for the thermal analysis of our design of a nuclear micro-reactor, addressing the challenges of efficient heat management and safety in compact reactor designs. We introduce an approach that integrates computational fluid dynamics and thermal-hydraulic simulation, for the constraints and operational parameters of micro-reactors.

Our methodology highlights the factors that influence micro-reactor thermal performance, including coolant flow rate, temperature, geometric configuration, and heat transfer. We further explore the implications of our findings for reactor design, emphasizing the importance of thermal efficiency and safety margins in the development of advanced nuclear micro-reactors.

Significantly, our work not only contributes to the optimization of micro-reactor designs but also provides a framework for future research in nuclear reactor thermal analysis. The implications of our study extend to the broader field of nuclear engineering, offering valuable insights into the safe, efficient, and sustainable deployment of nuclear micro-reactors.

KEYWORDS: nuclear, micro-reactor, thermal analysis, CFD, methodology

1. INTRODUCTION

The global search for sustainable and dependable sources of energy has rekindled the importance of nuclear power as a significant constituent of the energy mix. Nuclear micro-reactors are emerging as a solution to this challenge, providing a combination of compactness, scalability, and the ability to produce power in remote locations or for specialized applications, such as space exploration. However, the design and operation of these reactors come with unique challenges, particularly in thermal management and safety. Precise thermal analysis is critical to ensuring operational efficiency and preventing overheating, which could result in nuclear safety hazards.

This article presents a methodology for thermal analysis of nuclear micro-reactors that builds upon existing knowledge in the field while addressing the specific challenges presented by the small size and unique operational conditions of our model. This study provides a framework for estimating the thermal behaviour of our model of a nuclear micro-reactor under defined conditions, using computational fluid dynamics simulation software. The goal is to optimize the reactor design and improve our engineering practice, ensuring that our model can meet the potential as a secure and efficient energy source for the future.

2. LITERATURE REVIEW

In [1], Zhang et al. presents an approach to modelling a micro gas-cooled nuclear reactor using the Modelica language, covering reactor system designs, heat engine systems, and control systems. It details the development of a reactor neutron model based on point reactor neutron dynamics, thermal-hydraulic models, and the use of external C functions for decay heat models, highlighting the importance of fuel temperature coefficients and xenon-135's impact on reactivity. [1]

The study [2] also discusses the multiphysics analysis of a megawatt heat pipe reactor moderated by metal hydride and utilizes burnable poisons for controlling reactivity. It assesses burnable poison materials' performance, evaluates different moderator materials under accident conditions, and uses OpenMC for neutronic modelling. This work emphasizes the need for safety analysis and performance assessment in the design of micro-reactors. [2]

Argonne National Laboratory's report [3] , discusses various micro-reactor designs under development, focusing on gas-cooled or heat-pipe concepts. It presents the challenges in modelling and simulation for micro-reactors and describes high-fidelity multi-physics simulations for heat-pipe micro-reactor concepts. [3]

In [4] the authors introduce reduced-order modelling (ROM) based on Proper Orthogonal Decomposition (POD) for thermal analysis of gas-cooled microreactor cores. It explains the calculation of POD basis and coefficients, offering a different approach to analyse the thermal behaviour of microreactors with reduced computational costs. [4]

3. DESIGN PARAMETERS

The design is based on previous work performed in Ansys SpaceClaim. [8] There were several iterations of 3D designs that were considered for the project. After we underwent several iterations through optimizing the heat exchange surfaces and flow paths. [8] The nuclear micro-reactor vessels that is proposed as an innovative design is presented in Figure 1. The main geometric parameters of the CAD model presented in Fig.1 are:

- Length approx. 500 mm;
- Outer diameter: 250mm;
- Inner diameter: 240mm;

This is the model used for subsequent thermal analysis.

The model presented in Figure 1 is comprised of 32 pipes having 7mm in diameter, they are distributed along the radius of the vessel and 9 pipes with a 32mm diameter. The 32 mm pipes provide a higher flow there for it evacuates more heat from the core. The smaller pipes have increased heat exchange surface by design and are used to their full potential.

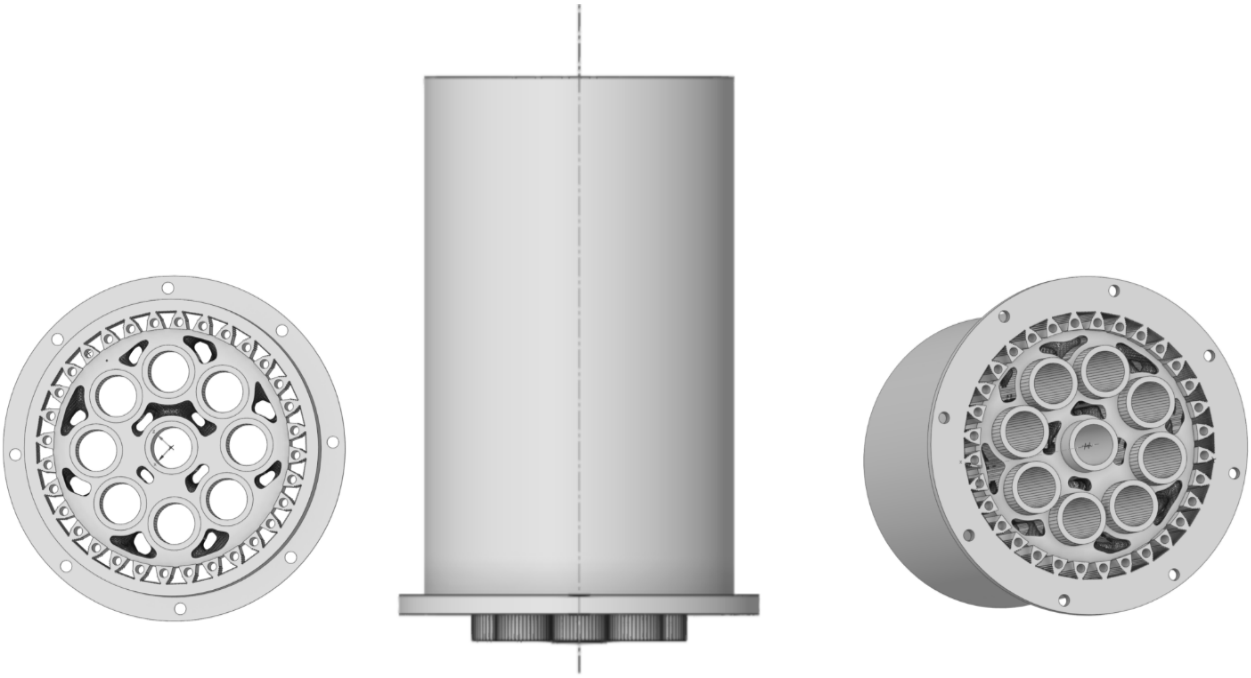

Figure 1. CAD model for analysis

Table 1. SS316L Material Properties [6][7]

Property	Value	Unit
Density	8.0	g/cm³ (0.289 lb/in³)
Melting Point	1375-1400	°C (2500-2550 °F)
Yield Strength (0.2%)	170 (Min, Hot Finished), 310 (Min, Cold Finished)	MPa (25 ksi, 45 ksi)
Tensile Strength	485 (Min, Hot Finished), 620 (Min, Cold Finished)	MPa (70 ksi, 90 ksi)
Elongation	40, 30	% (in 50 mm)
Thermal Conductivity	16.3 at 100 °C, 21.5 at 500 °C	W/m·K
Specific Heat Capacity	500	J/kg·K (at 20 °C)
Electrical Resistivity	0.74	µΩ·m (at 20 °C)
Elastic Modulus (Modulus of Elasticity)	193	GPa (28 x 10^3 ksi)
Magnetic Permeability	1.01 (Approximate)	-
Rockwell Hardness (HRB)	Max 95	-
Brinell Hardness (HB)	Max 217	-

The material selected is Stainless Steel 316L which is a good option [9] due to its usability in the nuclear environment and compatibility with additive manufacturing technologies. The properties selected for this design are presented in Table 1. The heat transfer method is predominantly conduction, and the hypothesis is to take advantage of the heat pipe principle within the reactor vessel to distribute the heat evenly. This consists of a fluid within the vessel contained in a low pressure, low pressure compared to the initial considered pressure in the main cooling pipes of 50 bar, enough to permit the steam to travel across the vessel, to the point it gets cooled and returns in a cooled liquid form. This is possible through the small fins provided by the design.

For the working fluid, we chose water (Table 2) [11] as it is an accessible material that can provide feedback in the validation process and can provide a good balance between the quantity of fluid and heat capacity as presented in Table 3 and Figure 2. The necessary quantity of fluid required to evacuate 2 MW of heat using different cooling agents, the basic heat transfer formula provides enough information to select the optimum coolant for our model.

$$Q=mcp\Delta T$$

where:

- Q is the heat transfer rate in watts (W),
- m is the mass flow rate in kilograms per second (kg/s),
- cp is the specific heat capacity in joules per kilogram Kelvin (J/kgK),
- ΔT is the temperature change in Kelvin (K).

Given 2,000,000 W (2 MW), we calculated the mass flow rate (m) for each coolant, assuming a reasonable temperature rise ($\Delta T \Delta T$) of 10 K to further simplify the calculations. Based on this simple formula and assumptions the following flow rates resulted:

- **(H_2O)** $m \approx 47.62$kg/s
- **(D_2O)** $m \approx 47.62$kg/s
- **(Na)** $m \approx 153.85$kg/s
- **(CO_2)** $m \approx 250$kg/s
- **(He)** $m \approx 38.46$kg/s

Based on the results presented above we estimated the necessary quantities of fluid for each considered cooling agent. The information presented in Table 2 is provided from the open-source information website https://tpsx.arc.nasa.gov/ and compared with the existing ANSYS database within the software. [11] [12]

In Table 3 we presented the material properties of cooling agents used in the nuclear industry. The most common agents used are water and heavy water, followed by air, liquid sodium, carbon dioxide, helium, and others in newer innovative designs. Public information is limited as the newer technology is undergoing further test and validation. [13] These types of coolant agents vary depending on technology used, reactor power, temperature of fuel, type of fuel, material properties of fuel elements, chemistry considerations and so forth. Selecting the right coolant is important as this influences all aspects of the reactor from the design stage up to operations, even after decommissioning. The cooling agent becomes radioactive and needs special considerations for storage and safeguards.

Furthermore, in Figure 3 the mesh of the pipe is presented, it shows the attention to detail allocated both for heat transfer and fluid flow at a reasonable level. This distribution of the mesh nodes and elements was selected for all pipes regardless of diameter.

Table 1. Material Properties of Cooling Agents in Nuclear Reactors [11]

Cooling Agent	Thermal Conductivity	Specific Heat Capacity	Boiling Point	Operating Pressure	Chemical Reactivity
Light Water (H_2O)	0.6 W/mK	4.2 kJ/kgK	100 °C at 1 atm	High (Pressurized)	Low
Heavy Water (D_2O)	0.6 W/mK	4.2 kJ/kgK	101.4 °C at 1 atm	High (Pressurized)	Low
Liquid Sodium (Na)	130 W/mK	1.3 kJ/kgK	883 °C	Low (Atmospheric)	High (with Water)
Carbon Dioxide (CO_2)	0.016 W/mK	0.8 kJ/kgK	-78.5 °C (sublimes)	High	Non-Combustible
Helium (He)	0.15 W/mK	5.2 kJ/kgK	-268.9 °C (at 1 atm)	High	Inert

Table 2. Material Properties of Cooling Agents in Nuclear Reactors [5]

Cooling Agent	Specific Heat Capacity (kJ/kgK)	Necessary Quantity (kg)
Light Water (H_2O)	4,2	1714286
Heavy Water (D_2O)	4,2	1714286
Liquid Sodium (Na)	1,3	5538462
Carbon Dioxide (CO_2)	0,8	9000000
Helium (He)	5,2	1384615

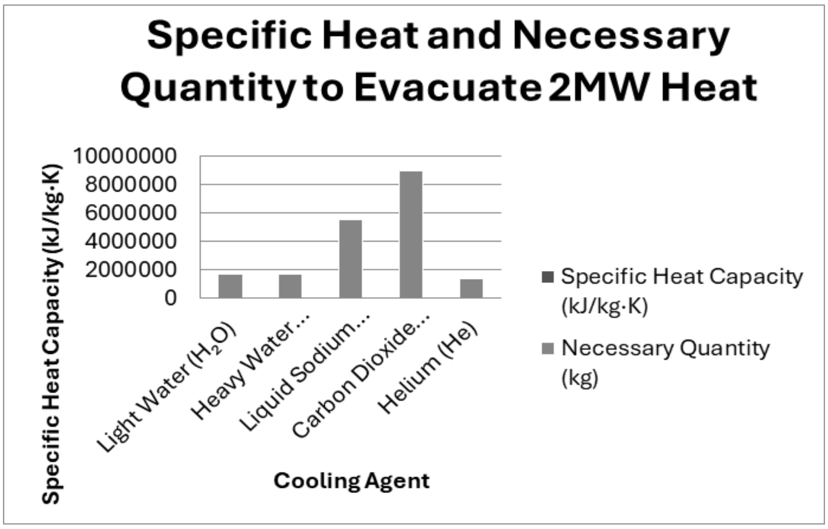

Figure 2. Comparison of heat capacity and required quantity of material to evacuate 2MW of thermal heat

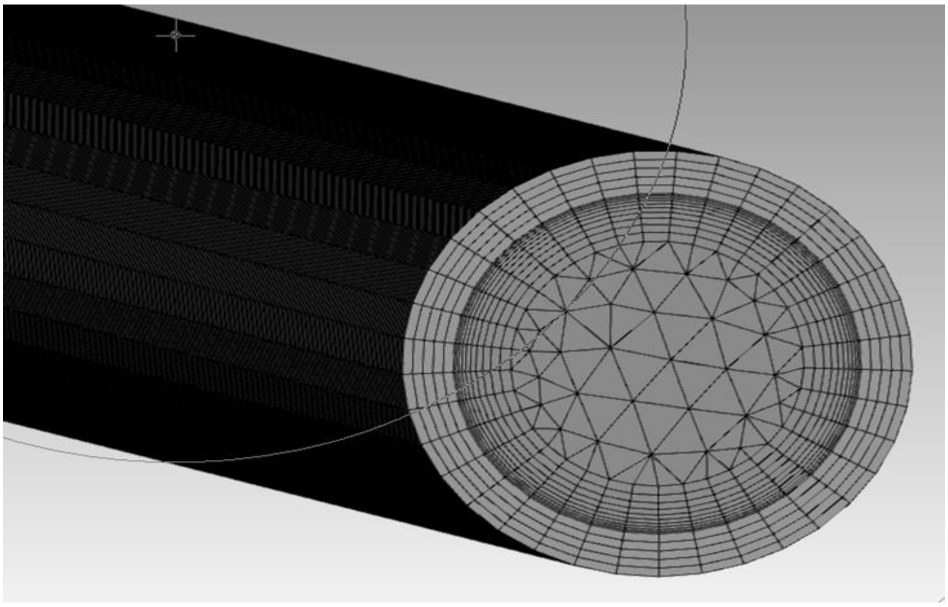

Figure 3. Mesh used for analysis

4. METHODOLOGY

The methodology selected is based on the simple principle that enough heat must be evacuated to cool down 2MW and maintain the reactor core temperature constant. This is important because increasing the temperature further would heat the material and cause structural deformations or even degradation of geometry.

Cooling the reactor can be done through several methods. [10] In this paper, we discuss the cooling of the core through the pipes that pass through it, according to the design presented in Figure 1. The pipes that pass through, based on diameter are of several types, with diameters ranging from 5 mm to 35mm. In this design, we highlighted the 7 mm ones with an average length of 420 mm. The reason for selecting the 7mm pipes is that most of our designs focus on these types of pipes. For this analysis we used k-epsilon turbulence model using standard wall functions.

The analysis was performed in Ansys Fluent CFD [12] with the following boundary conditions:
The temperature on the pipe's outer diameter is 600°C.
Model pipe diameter 7 mm.
Fluid velocity is 1.5 m.
Pressure of working fluid is 50 bar.
Initial temperature of fluid is 280°C.
Phase change not considered.
Heating through radiation not considered.
Number of iterations: 500.

5. RESULTS

We will present below the results of the Ansys Fluent analysis of the pipe model with 7 mm in diameter, including the mesh model used for analysis.

In Figure 4 is presented the temperature distribution across the pipe. The time step method is automatic using a time scale value of 1, this means it is a pseudo transient analysis that runs an iteration for as long as it is required by the boundary conditions to get a converged solution. The inlet fluid velocity was selected at 1.5m/s, this is an average value considering the fact that we have not selected the pumps that would circulate it. This value is also dependant on the diameter of the pipe, the required mass flow, and the amount of heat that we aim to extract. This value will be further refined for the final model. [14]

In Table 4 there are presented the values resulted from the analysis, an average temperature difference of 65 °C is a good indicator that the selected velocity is good, also having the same value for velocity at the outlet is also a good indicator. Loss of velocity towards the pipe surface is a normal effect and validates the mesh selection. The velocity phenomena can be observed in Figure 5, it is in accordance with expected values.

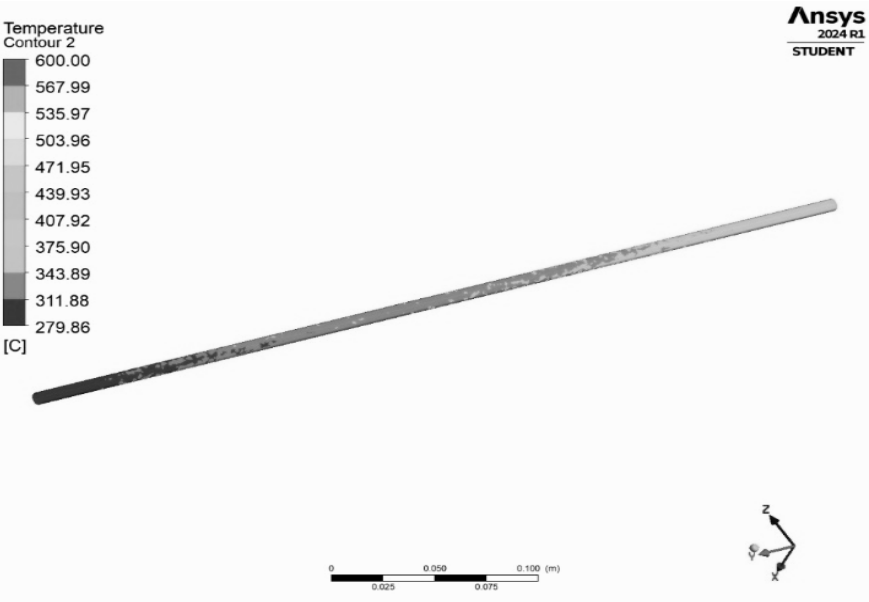

Figure 4. Average temperature distribution on the 7 mm pipe

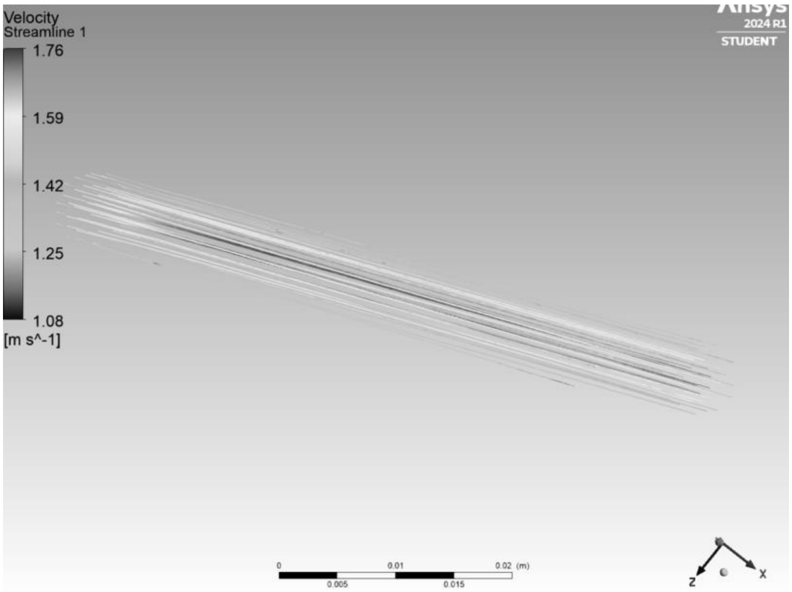

Figure 5. Distribution of velocity through the 7mm pipe with 600 C temperature on the outer surface of the pipe

Table 3. Average parameter values throughout the pipe

	Temperature	Velocity
Inlet	280.0°C	1.5m/s
Outlet	345.0°C	1.5 m/s
Wall and Fluid contact surface	521.6°C	1.194m/s
Fluid	317.65°C	1.466m/s

6. CONCLUSIONS

Although the working fluids density and phase are expected to change, we did the initial analysis without these variables as we consider that within 420mm they would not change too much to influence the results. For future work, we will select 100 bars as working pressure to avoid unwanted phase change and to limit uncertainties.

With an average temperature gain of 65°C, the modelled pipe is a feasible product. Considering we have 32 pipes distributed across the vessel. This would mean an average heat flux of 577kW.

Although this is a good number considering the size of the pipes and length through the core, we still would need to evacuate 1.5 MW of thermal heat.

For future work, we need to consider the bigger diameter pipes to be able to reach the 2MW milestone we have set. Also modelling various pipe models with density change enabled and at a higher pressure of 100 bar would provide a better understanding of the phenomena.

This paper concludes that the material and working fluids are feasible products to be used in further analysis as a heat flux of 577 kW is a good value for the length and diameter of selected pipes. This heatflux combined with the heatflux provided by the 32 mm pipes show promise of a successful model. This needs to be confirmed through a more complex analysis.

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