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DESIGN OPTIMIZATION METHODS FOR CONCEPTUAL DESIGN OF NUCLEAR MICROREACTOR

Constantin Alex SUMANARIU, Catalin Gheorghe AMZA

Abstract: *This work examines the optimization techniques that can be employed in the construction of nuclear microreactors. A successful model would have the advantage of enabling the efficient distribution of energy to remote communities or facilities. Given their large size and the need for safety precautions, this subject requires creative solutions and additional research. We explore the specific optimization strategies for thermal management and the effective removal of heat from the core, which is a crucial element of every nuclear reactor core.*

Key words: *conceptual, design, optimization, nuclear, microreactor*

1. INTRODUCTION

In the field of engineering and innovation, the optimisation of design is a component that significantly influences the development of efficient solutions. During the initial phases of design, optimisation concepts have a significant impact. This article will concentrate on a conceptual design specifically created to function in a nuclear environment.

Our objective is to explore the various possibilities for enhancing the performance of a Computer-Aided Design (CAD) model [1].

When developing microreactors, it is crucial to take into account multiple restrictions. The heat exchanger must optimise its utilisation of the little space available, given the compact dimensions of the reactors.

The heat exchanger needs to be efficient in its use of its available space due to the small size of the reactors. Despite their small size, microreactors may be able to generate significant amounts of heat, so the heat exchanger needs to be able to handle high thermal loads. The design needs to ensure that the reactor operates safely within temperature and pressure operating limits and to ensure longevity and consistent performance, the heat exchanger has to be designed to resist corrosion and minimize fouling, which means restriction of flow and creating a more difficult environment for heat transfer.

The articles reviewed also address the challenges faced in optimizing heat exchanger designs. By utilizing modern optimization techniques and drawing from recent literature, specific recommendations were used to optimize key parameters in heat exchanger design. This approach will ensure the optimization of each aspect of the design.

Presented in Fig. 1 is a section view of the start point for the CAD model. From this model, we start with the basic assumptions and move toward identifying an appropriate algorithm that is suitable for our model.

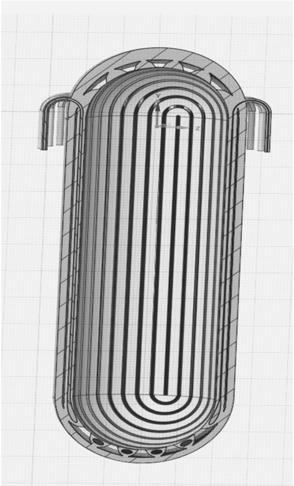

Fig. 1. Section View of Conceptual Design

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2. LITERATURE REVIEW

Before initiating the optimisation process, a analysis of the literature was undertaken to examine the optimisation pertaining to heat exchangers.

Recently, there has been a recognition of the importance of employing CAD tools to design and optimise heat exchangers. This chapter presents a selection of the research in this topic, focused on the methodologies and outcomes of significant studies that were identified.

Bolfo et al. conducted a study to investigate the potential of nuclear energy for hydrogen synthesis. I created and validated a computer-aided design (CAD) and computational fluid dynamics (CFD) model for a heat exchanger utilised at a nuclear power plant located in Japan. The model was improved by incorporating more materials and a specific primary coolant [2].

3D printing has fundamentally transformed the methods by which design and manufacturing procedures are carried out. Arrivabeni et al. (2021) presented an approach that successfully integrated 3D printing, CAD, and CFD to optimise the design of mould conformal cooling channels, as evidenced in their latest research. The researchers suggested a design methodology that conceptualised cooling channels using computer-aided design (CAD), evaluated them using computational fluid dynamics (CFD), and subsequently refined the design. This purpose and approach facilitated an examination of the cooling system. Following the completion of testing on a heat exchanger trial setup, the ultimate design was fabricated using 3D printing technology. This resulted in receiving useful input from the measurements, which was subsequently utilised to include additional enhancements. The user's text is enclosed in tags.

Chen et al. (2022) sought to improve the effectiveness of a plate heat exchanger by implementing a zigzag flow channel configuration. The research of Taguchi discussed a technique to determine the optimal operational parameters of the heat exchanger focusing on efficacy. In addition, the geometry was optimized using a genetic algorithm, with the key goals being to achieve a balance between efficiency and pressure drop [4].

Kim (2022) examined the procedure for enhancing the design of a compact heat exchanger that is specifically tailored for an energy recovery ventilator. The authors of the study determined the necessary parameters for the design phase of the heat exchanger. A refined design and approach were suggested, incorporating a mathematical model based on empirical findings [5].

In their study, Cao et al. (2021) examined the process of optimising the design of a plate-fin heat exchanger for a combined cycle system. The study proposed a non-dominated sorting evolutionary algorithm to optimise different aspects associated with the geometry of the fins, including the number of fin layers and the plate width. The study introduced an approach that enabled the identification of the optimal choice for fins [6].

Aiello et al. (2021) introduced a technique for enhancing the design of a heat and mass exchanger. Their analysis highlighted the challenges arising from fouling, utilising empirical data. The researchers created a thermal model that incorporates the changes in pressure during the operation. The results emphasise the significance of taking into account fouling effects at the individual component level to maintain the performance of the heat pump over time [7].

Zhang et al. (2022) introduced an innovative heat exchanger design, which was influenced by the concept of bionic non-smooth surfaces. Their study attempted to reduce the resistance of fluid flow through the heat exchanger by optimising structural factors such as diameter, slot pitch, and groove depth. According to their statement, the fluid resistance could be decreased by up to 13% in comparison to traditional designs [8].

In their study, Bakr et al. (2022) proposed a genetic algorithm to optimize the arrangement of a shell and tube heat exchanger with the goal to optimize the heat transfer rate while limiting pressure drop. The article analysed the operating efficiency of heat exchangers, and proposed improvements that led to an average increase in effectiveness of 55% [9].

The review indicates that the publications discovered thus far primarily employed genetic algorithms, encompassing both conventional and non-dominated sorting variations, for the objective of optimisation. We utilised advanced modelling approaches, sophisticated decision-making processes, and unique bionic design principles to optimise heat exchanger designs and achieve superior results. Every essay emphasised the need of taking into account future work in connection to the length of the design process, which is affected by the thoroughness of the original requirements and, more importantly, the level of specificity in the design parameters.

3. METHODOLOGY

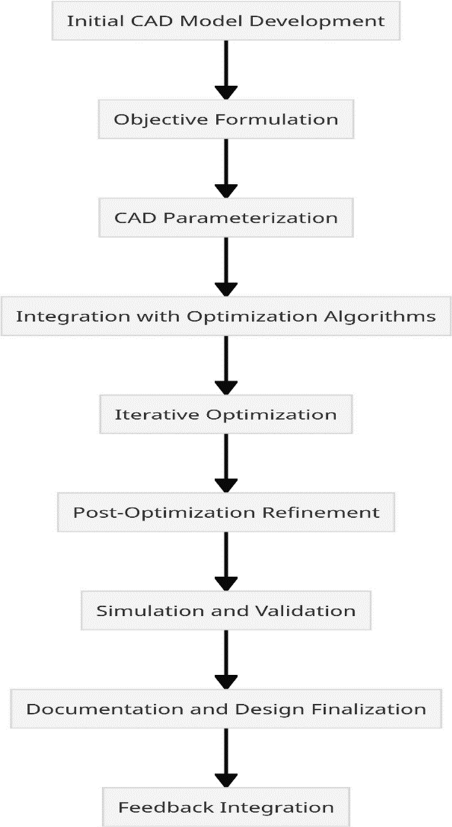

Fig. 2. Methodology Diagram

The methodology presents a recommended strategy for improving the computer-aided design (CAD) heat exchanger model. The suggested model is a CAD representation of the heat exchanger, encompassing elements such as tubes, fins, and the shell. Our design objectives are explicitly outlined, prioritising issues such as the dimensions of the model, simplicity of production, and thermal dissipation.

In the CAD environment, we initially determine crucial design parameters such as tube length and fin density. We ensure the incorporation of limitations to fulfil the necessary manufacturing and design criteria. Integration of the CAD software with an optimisation tool is necessary to enable automatic design adjustments based on optimisation outcomes. The optimisation method functions repeatedly within the CAD framework, providing real-time visualisation to guarantee adherence to restrictions and feasibility requirements. Once the ideal design is achieved, manual adjustments are made to guarantee that the design meets the initial specifications.

Our proposal suggests utilising the simulation modules inside the CAD platform to test the design, specifically for thermal analysis purposes.

After the CAD model has been optimised, the design documentation is created. Performance feedback on the design is gathered subsequent to manufacturing and deployment in order to provide insights for future revisions and enhancements.

This approach integrates computer-aided design (CAD) tools with optimisation algorithms to establish a streamlined and effective design process for heat exchangers. This technique guarantees unique and practical ideas by placing emphasis on iterative design, validation, and feedback [12-19].

Figure 2 illustrates that the optimisation process is dependent on multiple iterations, and the number of iterations can vary based on the level of strictness chosen for the optimisation algorithms.

4. INITIAL CONDITIONS

The conceptual design specifications of a vessel that is designed to facilitate heat transfer is presented in this section, with Stainless Steel 316L as the material of choice for the vessel due to its corrosion resistance and robustness, which render it appropriate for use in a nuclear environment. One of the vessel's distinctive characteristics is its circular piping system, which comprises 16 pipelines, each with its own inlet and outlet. We selected the optimal quantity of pipes that would accommodate the given diameter.

One may notice a variation in vessel thickness, this is due to the increasing heat exchange surface area for the pipes.

Physical Dimensions [1]:

Vessel Mass: 76,9689 kg

Height: 0,25 mm

Width: 0,25 m (0,29 m – including pipes)

Length: 0,7839 m

Volume Specifications:

Vessel Interior Volume: 0,0241 m^3

Piping Total Volume: 0,0011 m^3

Estimated Volume of Fluid: 0,0251 m^2

Material and Density:

Vessel Material: Stainless Steel 316L

Vessel Material Density: 8000 kg/m^3

Working Fluid Options:

Working Fluid: Water or Helium (Not defined yet)

Fluid Specifications:

Estimated Water Mass within the Volume: 25,2203 Kg

Total Fluid Surface Area: 2,613 m^2

Estimated Gas (Helium) Mass within the Volume: 0,0041 Kg

Piping Details:

Piping Information: 16 pipes with 16 inlets and 16 outlets arranged in a circular pattern.

Pipe Interior Diameter: 7,5 mm

Vessel Thickness:

Vessel Maximum Thickness: 13,2856 mm

Vessel Minimum Thickness: 2.17 mm

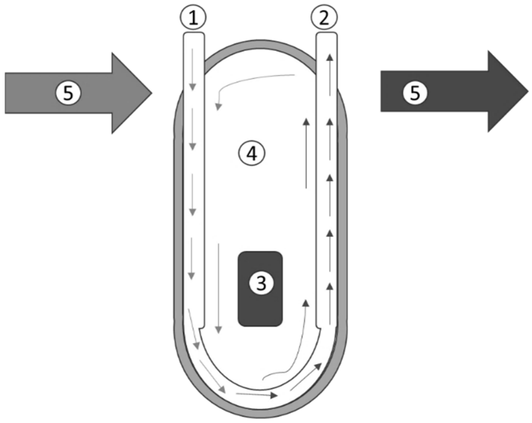

Fig. 3. The theoretical thermal layout of the model: (1) Cooling pipes inlet, (2) Cooling pipes outlet, (3) Reactor core, (4) Interior vessel natural circulation, (5) External cooling method

The model has an initial thermal layout that provides the starting point for thermal analysis. This provides the operating assumptions and will change over time based on results from thermal or other functional analyses. The thermal layout is presented in Figure 3.

5. OBJECTIVE FORMULATION

The primary goal of the model is to effectively evacuate a minimum of 2MW of thermal heat through the cooling fluid at a pressure of up to 100 bar.

In order to accurately evaluate the present heat dissipation capability, we conducted multiple iterations of this model and compared them to other modifications.

6. CAD PARAMETRIZATION

The CAD parametrization purpose is to determine a model that is appropriate for extracting heat from the fluid that is flowing through the pipelines. The model and characteristics that most accurately aligned with the anticipated outcome were determined using mathematical computations.

The quantitative computations were conducted using the heat transfer formula for heat exchangers, which is derived from the fundamental concept of energy conservation.

$$(\mathrm{W})Q = UA\Delta\mathrm{T}$$

The amount of heat transferred per unit of time is represented by the symbol Q, measured in watts (W). The overall heat transfer coefficient, U, is measured in watts per square meter per kelvin ($W/m^2 \cdot K$). The surface area through which the heat is transferred is denoted by the letter A and is measured in square meters (m^2).

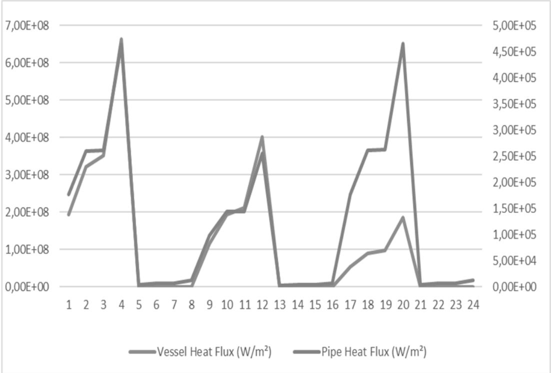

Fig. 4. Vessel and pipe heat flux comparison

While the calculations were made using the fundamental principle of conservation of energy the CFD program used as a standard the k-epsilon model for calculations. The k-epsilon model is more focused on turbulent flows, and it an provide a useful tool as heat exchangers rely on turbulent flows to increase heat transfer.

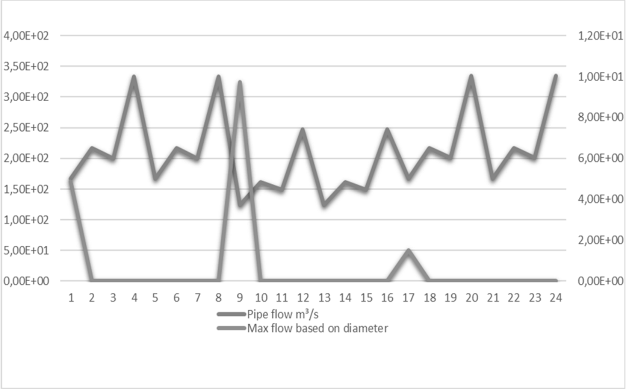

Fig. 5. Comparison of required pipe flow and maximum flow based on pipe diameter.

The difference observed between Vessel heat flux and pipe heat flux presented in Figure 3 is normal due to the volume that is occupied by the fluid within the pipes compared to the volume of the vessel.

In Figure 5 there are noticeable discrepancies between the allowed flow based on diameter and the required flow to evacuate the required amount of heat.

To confirm the results of this calculation we made a simulation using ANSYS Workbench and Discovery, as it proves to be a fast and reliable confirmation tool.

Table 1. Maximum velocity results from simulation

Iteration	Convection (W/m^2·°C)	Flow Inlet (°C)	Flow Outlet (Pa)	Max Velocity (m/s)	Max. Temperature (°C)
DV1	15	300	1e5	0,191	400
DV2	16,5	300	1e5	0,219	400
DV3	19,5	300	1e5	0,196	400
DV4	22,5	300	1e5	0,191	400

The results that are presented in Table 1 were a direct output of several variations of the convection values on the pipe with the shortest length, which is presented in Figure. 5.

We chose the smallest pipe for faster simulation results and for the simple hypothesis that if the smallest pipe would have sufficient flow, then all pipes would. Within Figure 6 we highlighted the mesh type for the pipe model that we considered adequate for performing the simulation.

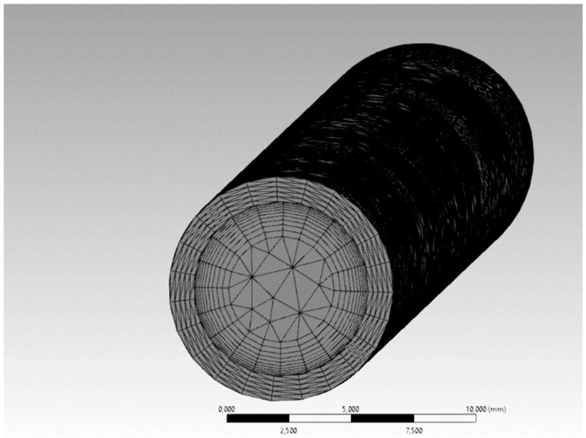

Fig. 6. The simulated pipe and mesh

Fig. 7. Pipe distribution across reactor vessel

7. IDENTIFIED ALGORITHMS

Several factors have to be taken into account in order to optimize heat exchangers, including tube dimensions, fin configuration, material choice, working fluid properties, and component arrangement. The tube diameter and length affect the efficiency of heat transfer while the configuration and spacing of fins also impact thermal conduction efficiency. This is why material thermal properties and durability are important for performance and lifespan. In addition to this, the working fluid velocity and flow direction affect efficiency while genetic algorithm (GA) can be used to select tube diameters and lengths that are optimal thus improving design effectiveness [34]. Bakr et al.'s study demonstrates that GA effectively explores different designs thereby identifying optimal combinations [5]. Furthermore, combining CFD models can reveal how tube dimensions influence fluid dynamics and heat transfer efficiency [10]. To ensure maximum long-term performance and safety of a heat exchanger, fouling must be considered by adopting Aiello's approach. Optimisation of fin spacing and arrangement, considering fouling, can enhance heat transfer efficiency and reduce fouling probability. Developing genetic algorithms (GA) will facilitate the evaluation of different fin shapes and spaces for achieving the best design on which to base heat transfer [8]. The material properties are important from the perspective of heat conduction and corrosion resistance in nuclear environments. Liangxing et al.'s method analyses the selection process for the most appropriate material for a heat exchanger, considering parameters like thermal conductivity, cost, manufacturability, and corrosion resistance [11]. To make fluid flow faster, a genetic algorithm (GA) may be used in combination with computational fluid dynamics (CFD) simulation. This allows for an examination of how different flow rates and directions affect both heat transfer and pressure drops. The Genetic Algorithm (GA) can determine the optimal balance among these factors, leading to very good results. According to the best results achieved so far, it is recommended to use hybrid techniques that involve utilising both computational fluid dynamics (CFD) simulations and genetic algorithms (GA). This approach improves both strength and thermal stability, much like fibres strengthen polymer matrices. Optimising the print orientation, layer thickness, and hatch spacing may provide advantages for the mechanical qualities and radiation resistance of the reactor vessel. Automated and regulated deposition processes can provide consistent material properties and reduce flaws in crucial components, such as reactor vessels. Nuclear applications can effectively manage waste and utilise resources through the recycling of materials, such as fibres. To assess the performance of composite materials, mechanical characterisation is required. When choosing materials for nuclear microreactor vessels, it is vital to carry out thorough testing to evaluate their thermal, mechanical, and radiation resistance properties [20].

8. ACKNOWLEDGEMENTS

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9. CONCLUSIONS

The best way to deal with the unique issues and needs of a nuclear microreactor vessel would be to use a hybrid approach that takes the best parts of different approaches. An efficient approach involves utilising computational techniques to optimise the design of heat exchangers. By combining computer-aided design (CAD) with optimisation algorithms, a systematic analysis of a wide range of design possibilities is achievable to verify that the final design fulfils the performance and safety standards. This approach utilises algorithms and iterative design methods, leading to improvements in the efficiency, safety, and cost-effectiveness of vital components. Therefore, to be visually attractive as well as manufacturable, these designs must incorporate real-time visualization, simulation modules and feedback loops.

The next study should thus explore how machine learning methods can be combined with CAD (computer aided design) tools that use simulations and data from known databases, standards and open sources to predict optimal design parameters. This would make optimization more efficient. With growing material sciences, there are possibilities for new materials or composites offering improved thermal conductivity, corrosion resistance, endurance. Moreover, these materials could be applied for better designs.

Although simulations may provide deep insights into given problems, but practical applicability requires testing optimised designs in real environments. Thus, following studies should focus on creating and evaluating such ideas through practical experiments in natural settings. Furthermore, multi-objective optimization has a potential for future inquiry in terms of conflicting objectives between them (e.g. cost-efficiency-lifetime).

With the rise in computer capacity, it becomes possible to combine more sophisticated simulation modules that can accurately mimic intricate physical phenomena, including turbulence, fouling, and transient behaviours. Further research could also examine the ecological consequences of heat exchanger configurations, to optimise carbon footprints and environmental sustainability.

It is worth exploring collaborative CAD platforms that allow for the simultaneous involvement of several specialists in the design process, as it would ensure that a holistic design approach is taken, if professionals from several disciplines are involved in the design process.

For additional information on how pipes perform in confined spaces at such circumstances, more investigations on finite element method (FEM) analysis targeting temperature and stress factors could be useful. However, the findings of the study should be checked through empirical experimentation.

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Metode de optimizare a designului pentru proiectarea conceptuală a microreactoarelor nucleare

Acest articol discută metodele de optimizare care pot fi utilizate în dezvoltarea microreactoarelor nucleare, valoarea adăugată a unui model de succes fiind că ar asigura distribuția energiei electrice sau termice pentru comunități sau instalații izolate. Datorită dimensiunilor lor reduse și a considerentelor de siguranță, strategii inovatoare sunt necesare și este nevoie de mai multă muncă în acest domeniu. Discutăm tehnicile de optimizare identificate pentru gestionarea termică și evacuarea eficientă a căldurii din zona activă, acest aspect fiind vital oricărui reactor nuclear.

Constantin Alex SUMANARIU, student doctorand, Universitatea Națională de Știință şi Tehnologie Politehnica Bucureşti, Facultatea de Inginerie Industrială și Robotică, sumanariuc@yahoo.com, +40731639070.

Catalin Gheorghe AMZA, Prof.dr.ing, conducător de doctorat, Universitatea Națională de Știință şi Tehnologie Politehnica Bucureşti, Facultatea de Inginerie Industrială și Robotică, acata1@camis.pub.ro, +40744500803