TFPA PhD FIRST YEAR FINAL REPORT

Development and optimization of components for thermal control in the field of nuclear fusion and fundamental research in Physics and Astrophysics through metal additive manufacturing

PhD Program: Tecnologie Per La Ricerca Fondamentale In Fisica E Astrofisica (TFPA)

CURRICULUM: Meccanica

UNIVERSITY/RESEARCH CENTRE: Università degli Studi di Padova (DFA) / INFN sezione di Padova

PhD STUDENT: Francesca Valentini

SUPERVISOR: Prof. Simone Mancin

Padova, 05/09/2024

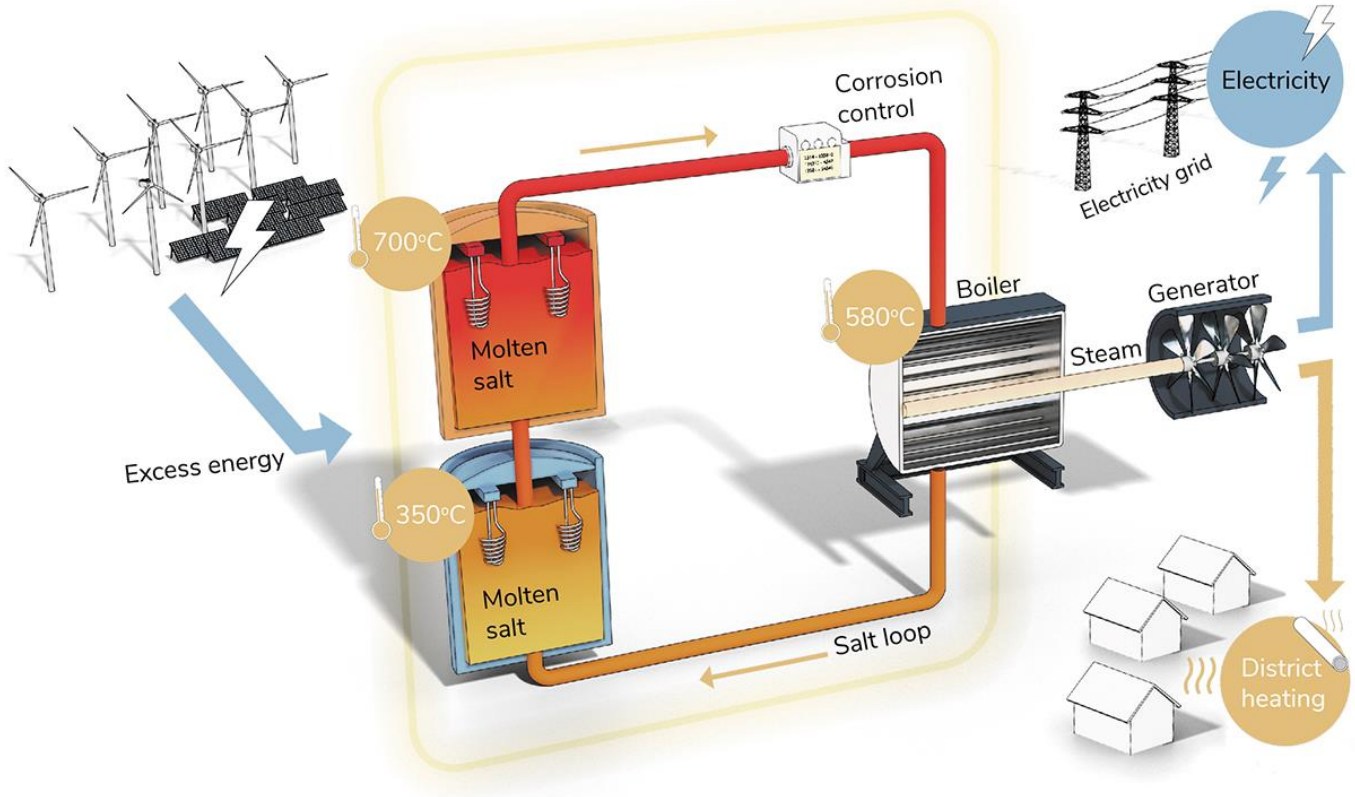
RESEARCH TOPIC AND OBJECTIVES

LoCoMoSa PROJECT (Low-Cost Molten Salt Thermal Energy Storage for Industrial Processes)

Research Topic:
Innovative Design and Optimization of Steam Generators for Thermal Energy Storage

Objectives:

- Design a steam generator for additive manufacturing (AM).
- Optimize the design for high-temperature applications (700-350 °C).
- Validate the design through experimental testing and data analysis.



PROJECT PLANNING

LoCoMoSa project (Low-Cost Molten Salt Thermal Energy Storage for Industrial Processes)

2023 - 2024

FIRST YEAR: Foundation & Preliminary Design

•Conduct an extensive literature review on steam generators for high-temperature applications.
•Study and evaluate optimization algorithms, in particular topology optimization.
•Develop a baseline steam generator design.
•Create an initial design incorporating insights from literature and initial optimization.

2024 - 2025

SECOND YEAR: Optimization & Experimentation

•Investigate alternative solutions
•Refine topology optimization models based on first-year research and future abroad experience.
•Build and calibrate an experimental setup to:
- Obtain a reliable boiling curve.
- Validate optimization results against empirical data.

2025 - 2026

THIRD YEAR: Final Design & Adaptation

•Iteratively improve the design using experimental feedback.
•Adapt design for a wide range of operational conditions.
•Finalize design and prepare for comprehensive testing or real-world application.

COURSES, EXAMS, AND OTHER TRAINING ACTIVITIES (E.G. SCHOOLS)

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2023 - 2024

COURSES

- Thermo-fluid dynamic sin 3D printed channels |TFPA
- Coupled electrical-thermal-structural Finite Element Analyses |UNIPD (DII)
- Experimental measurements in thermal fluid dynamics |UNIPD (DII)

COURSES (Non recognized)

- Thermal Management of electronic devices |Master D. (DTG)
- Applied Thermo-fluid Dynamics |Bachelor D. (DTG)

SCHOOL

- Summer School Metal Additive Manufacturing,
  Associazione Italiana di Metallurgia AIM, Bertinoro - 30 June, 1-2-3 July 2024

2024 - 2025

COURSES

- Metal Additive Manufacturing |TFPA
- Life Cycle Assessment of Energy Systems: fundamentals and applications |UNIPD (DII)

FIRST YEAR ACTIVITY

OUTLINE

1. Understanding AM
2. Choosing base steam generator geometry
3. Steam generator preliminary study and operative condition
4. Topology optimization study
5. Next steps

FIRST YEAR ACTIVITY: LITERATURE REVIEW

1- UNDERSTANDING ADDITIVE MANUFACTURING

Advantages:

- ✓ Design flexibility,
- ✓ Reduced number of welding joints,
- ✓ Simplifies the overall production process,
- ✓ Improved heat exchange efficiency

Limitations:

- χ High initial cost
- χ Limited building size
- χ Quality Control Challenges,
- χ Limitation in the design freedom

Innovative Steam Generator Design for AM

- Reduces material usage and size,
- Maximizes efficiency,
- Minimizes dead zones

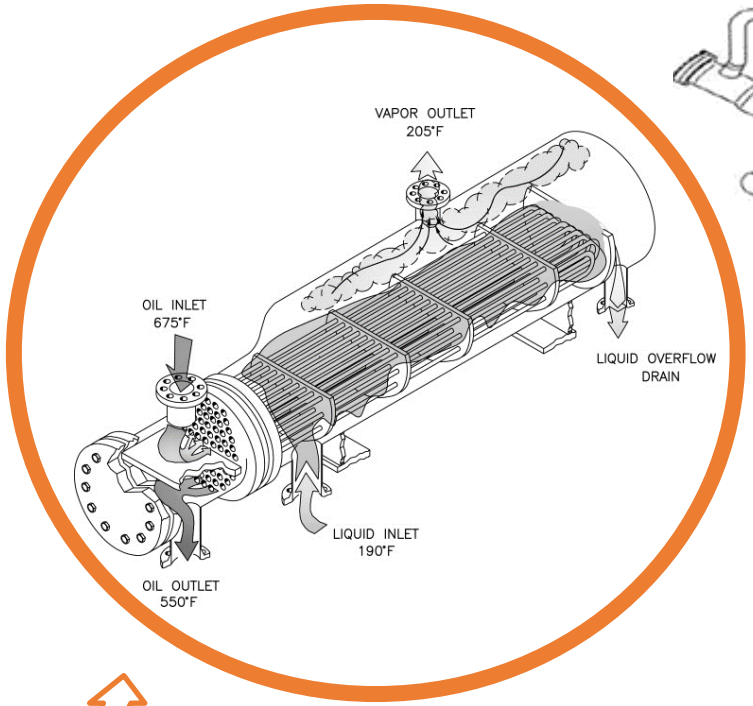
Powder bed fusion technology

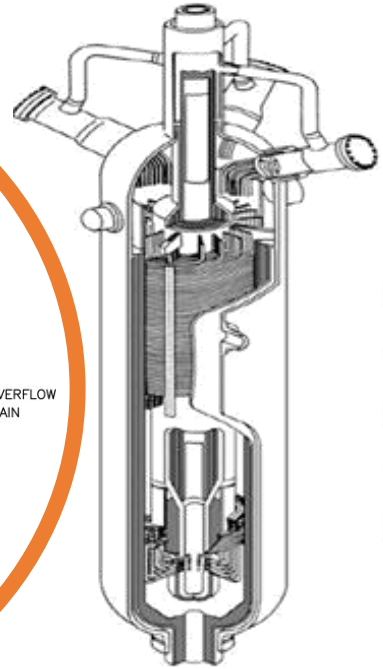
FIRST YEAR ACTIVITY

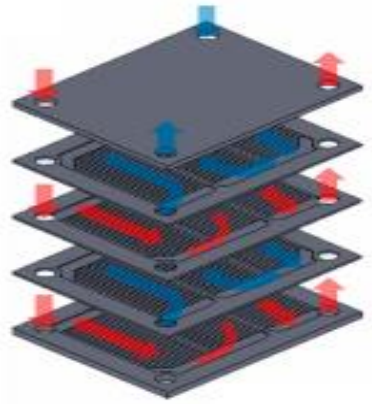
2- CHOOSING THE MOST SUITABLE INITIAL DESIGN

- **Considered Configurations:**
  - Conventional Kettle reboiler
  - Helical Coil Shell and Tube
  - Printed Circuit Heat Exchanger (PCHE)
  - etc.

- **The designs were evaluated based on:**
  - Compatibility with AM
  - Localized Stress
  - Corrosion Resistance
  - Ease of Inspection
  - Performance (Heat Transfer Rate)
  - Qualification/Codification
  - Cost







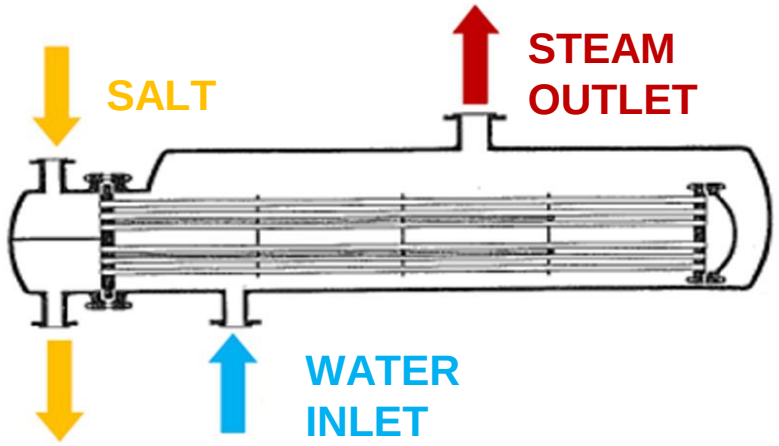
FIRST YEAR ACTIVITY

3- UNDERSTANDING THE OPERATIVE CONDITIONS

- The significant temperature difference between the molten salt and water sides makes the steam generator operate in a transition film boiling condition.

Salt (NaOH)

- Tin: 600°C
- Tout: 400°C
- P=1atm



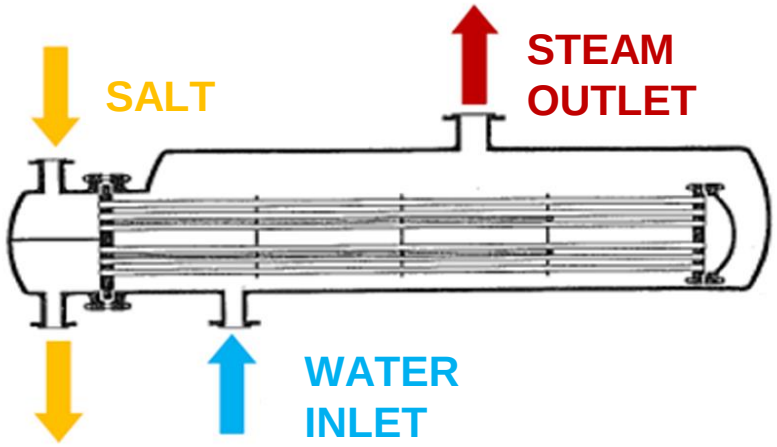
Saturated Water

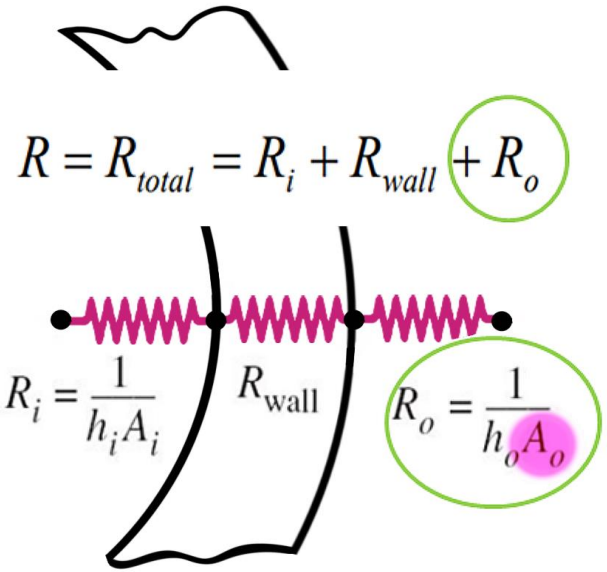
- T= 210°C
- P≈ 19 Bar

FIRST YEAR ACTIVITY

3- UNDERSTANDING THE OPERATIVE CONDITIONS

- The significant temperature difference between the molten salt and water sides makes the steam generator operate in a transition film boiling condition.
- To enhance efficiency, the key strategy is to increase the steam surface area by developing optimized fins.





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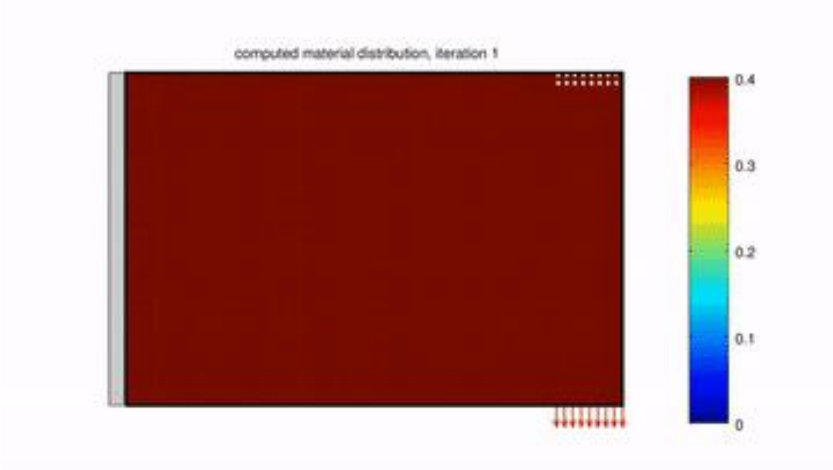
FIRST YEAR ACTIVITY

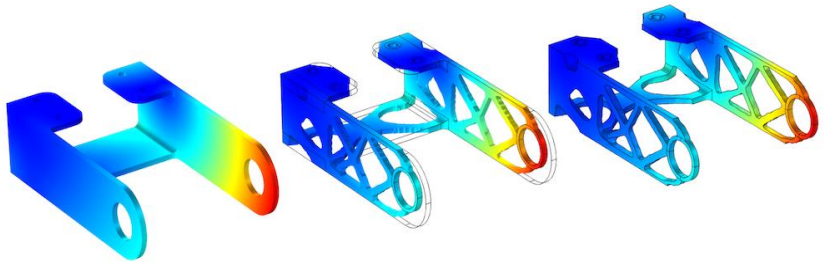
3- DEVELOPING OPTIMIZED TUBES

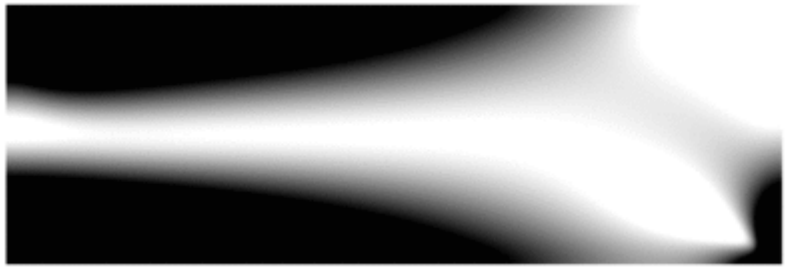
- Topological optimization (TO) was performed with the commercial software Comsol® to maximize the heat transfer during the nucleate boiling.
- Multiple TO solutions were designed



COMSOL

TOPOLOGY OPTIMIZATION MODULE





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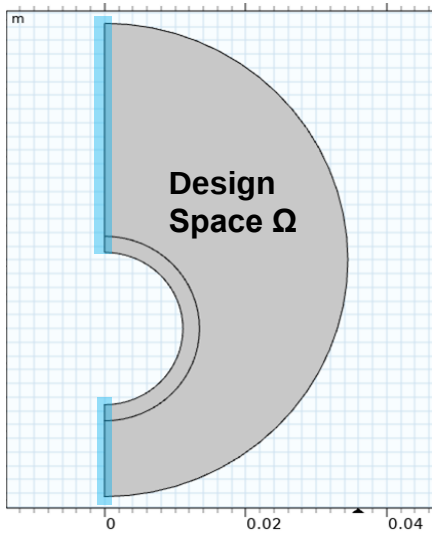
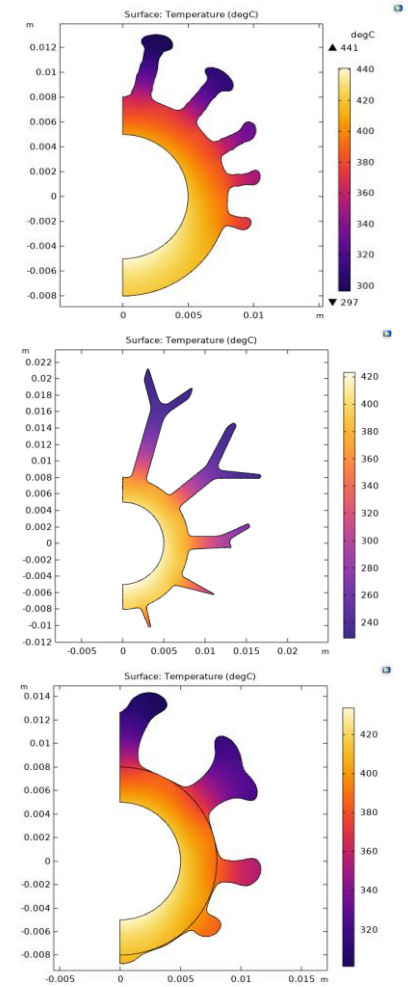


COMSOL

TOPOLOGY OPTIMIZATION MODULE

$$f = \int_{\Omega} \left[q \cdot k(\nabla T)^2 + (1-q)\frac{h_0 h_{max}}{A} |\nabla \theta(x)|^2 \right] d\Omega,$$

$$0 \le \int_{\Omega} \theta \, d\Omega \le \gamma$$



SECOND YEAR ACTIVITY

3- NEXT STEPS

Kettle-NaOH Problems:

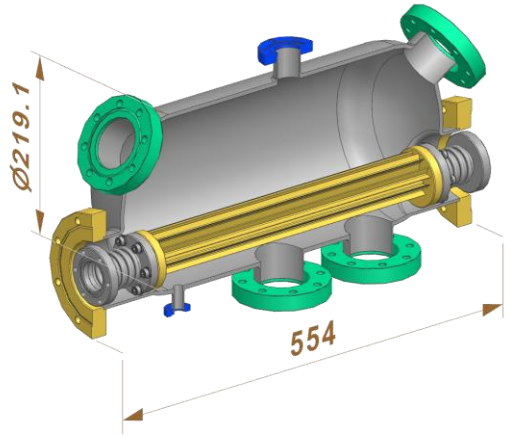
- Boiling uncertainty may cause significant HTC variations across the tube.
- High thermal stresses in the tube, especially during startup, could arise due to variable HTC.
- Risk of molten salt solidification if water-side HTC is higher than expected.

Model Limits:

- The model is still in its initial phase and many other factors needs to be included to have reliable and physically accurate geometries

Next step and solution

- Produce experimental test chamber to get reliable boiling correlation
- Develop an improved model that addresses the limits.
- Investigate possible alternative solution to Kettle reboiler.



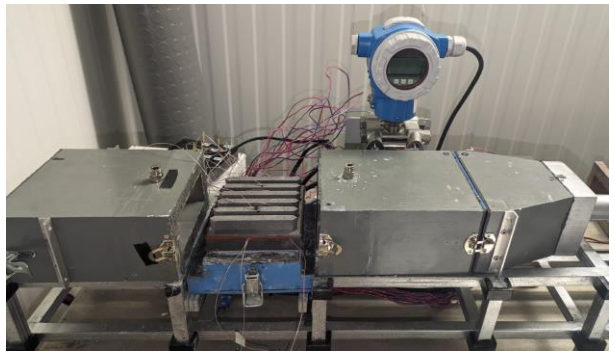
OTHER ACADEMIC RESEARCH

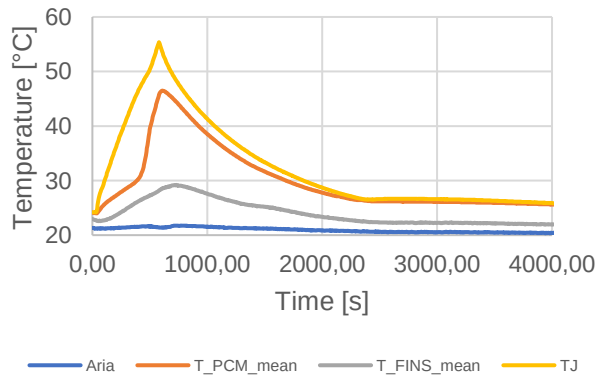
GEOMETRY OPTIMIZATION FOR ADDITIVE MANUFACTURING:

PCM filled Heat sinks for improved cooling performances of electric devices

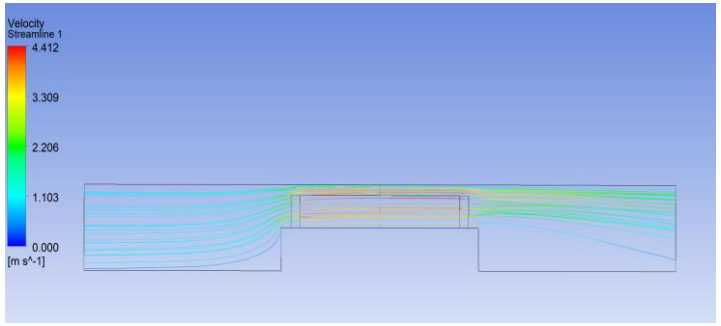
Heat sink bases with different geometries for enhancing thermal conductivity

PCM filling for power spike absorption and fins for dissipation





Experimental testing in wind tunnel



Experimental results will allow for tailoring simulations and produce novel future designs

Q&A

Thank you for your attention!

Questions?