Experimental and numerical study of a bayonet tube heat exchanger for decay heat removal in LFR

– PhD proposal –

(ID No. 1001138)

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***Keywords* —** Decay heat removal system, thermal-hydraulics, two-phase flow
***Topics* —** Simulation and physical modelling of reactor components, validation against experiments

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	1 November 2023
Duration	3 years

Context

*new*cleo is designing new lead-cooled fast reactors (LFR) pursuing compactness in design and safe operation at any operational condition. Decay heat released to the molten lead after shutdown is removed by dedicated components that can be active or passive (DHRS or decay heat removal system). New heat exchangers of the bayonet type, as known as dip coolers, are currently under development as passive components. They will be installed in the reactor pool, being fed with water as secondary fluid that falls by gravity from a tank placed on top of the pool.

An ample experimental program is starting in the second half of 2023 at the thermal-hydraulic laboratory of the Energy Department of the Politecnico di Torino with the goal of testing the mechanical and thermal-hydraulics performances of the prototype units. The experimental tests will be performed in realistic physical conditions to reproduce the expected behavior of the heat exchanger.

The candidate will develop numerical models of the component during this PhD program to support the design phase of the experiments and to interpret the experimental results.

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Description

After reactor shutdown, residual heat is still released from activated materials produced during normal operation. Although this source of thermal power is only a small fraction of the nominal power, it must be removed to prevent loss of integrity of the structures containing the radioactive materials, and in particular, to ensure the confinement of the fission products within the fuel rods. The DHRS can be made of different sub-systems working redundantly or in complementary way. In LFRs, typical DHRS are represented by Reactor Vessel Air Cooling System (RVACS) and dip coolers [1].

*new*cleo is working on innovative and passive heat exchangers of the bayonet type, capable of cooling down the molten lead that fills the reactor pool while avoiding lead freezing at the same time. Such exchangers are composed by a stack of shell and bayonet tubes submerged in lead (primary fluid). The secondary fluid is represented by water entering by gravity at atmospheric conditions, which is heated undergoing phase change, leaving then the bayonet tube as superheated steam.

An experimental campaign is planned at the thermal-hydraulic laboratory of the Department of Energy of the Politecnico di Torino to optimize the design of the exchangers and to verify the expected performances. The first goal of this campaign is to improve the thermal sizing of the component, verifying the assumptions made in terms of, e.g., critical quality and two-phase heat transfer coefficients. The tests will focus on both the steady state and transient component behavior, as well as on the start-up performance of the system, that is having cold water suddenly in contact with the hot bayonet walls. The campaign also aims at performing a hydraulic assessment of the bayonet tubes and of the DHR circuits, possibly identifying the conditions for the development of flow instabilities which might hinder the integrity of the component.

The present PhD proposal focuses on the analysis of the experimental data adopting numerical models of increasing complexity, starting from simple handbook equations and then moving towards 1-D system codes, such as AC2-ATHLET [2, 4, 3]. The availability of experimental data also represents an excellent opportunity for the development and validation of models coupling system level thermal-hydraulics (for the pipings) and CFD (for the bayonet tube itself), keeping in mind that two-phase CFD is currently a field of active scientific research, see for instance [5].

Quarterly reports will track the advancement and progress of the work. The preparation of scientific publications is requested as part of the research program.

Work plan

The first part of the work will be dedicated to a literature review regarding two-phase flow and heat transfer, focusing on the specific phenomena occurring in a bayonet-tube heat exchanger. Meanwhile, the candidate will participate to the setup and to the execution of the experiments, getting familiar with the system under study and analyzing the results as soon as they will become available.

To support the preliminary data analysis, the candidate will develop a simple Python code implementing two-phase flow and heat transfer correlations, relying on Python classes already present in the *new*cleo database. Afterwards, the candidate will use the advanced system code ATHLET to simulate the test cases, thus providing further insight on the experimental results, and possibly suggesting improvements to the models implemented in the code.

The final part of the work will be dedicated to the CFD simulation of the system. In view of the complexity associated with two-phase CFD modelling, this task could be carried out in a relevant institution during a 6-month period.

Preliminary actions for the work-plan:

- literature review on two-phase flow and heat transfer;
- development of numerical models for the simulation of the DHR component;
- participation to the experimental campaign;
- interpretation of the experimental results using the numerical models;
- investigation of possible bias and differences by recurring to more advanced models, like two-phase CFD;
- communication of the results on peer-reviewed journal and at scientific meetings.

Applicant profile

Master of Science in Nuclear, Mechanical or Aerospace Engineering.
Fundamentals in Computational Fluid Dynamics and Thermal-hydraulics.
Computer skills (already present or willing to learn): LaTeX, Python, bash, Linux-OS.

References

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Development of a subchannel code for full-core thermal-hydraulic analysis of lead-cooled fast reactors

– PhD proposal –

(ID No. 1000758)

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Keywords — subchannel method, full-core thermal-hydraulics, high-performance computing
Topics — Code development in support of core design

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	Last quarter of 2023
Duration	5–6 months

Context

*new*cleo is developing new Lead-cooled Fast Reactor units (LFR) and contributes to the development of advanced calculation schemes to reproduce numerically the behavior of fast reactors. Nuclear core calculations are necessarily multiphysics problems, showing often tight coupling between the different physical problems involved. High precision is sought by fine scale modeling, that is at the level of the single fuel elements, to achieve high-fidelity numerical simulations. This comes to a high computational cost that can be reduced by recurring to high-performance computing (HPC) exploiting parallel programming. Unfortunately, the upgrade of legacy computer codes with HPC is sometimes limited by the existing program structure.

Thermal-hydraulics at the level of the subchannels where the coolant flows is among the different physics treated in the coupled core calculations. The description of the flow and of the thermo-dynamics properties in every physical channel is computationally very expensive and challenging. Therefore, *new*cleo proposes a PhD program that focuses on the development a new computer code addressing this problem natively by HPC, and making use of the advanced features of FORTRAN 2018, like coarrays.

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Description

The design of Lead-cooled Fast Reactors (LFRs) currently under development at *new*cleo is a multidisciplinary task, dealing with many deeply interconnected physical and engineering parameters, thus resulting in a multiphysics coupled problem. This coupled problem can be logically subdivided into separate physical problems, with Thermo-Mechanics (TM), Thermal-Hydraulics (TH) and NEutronics (NE) as the three most relevant physics involved. Each physical problem is supported by purposely developed Design-Oriented Codes (DOCs) where a compromise between runtime performance and physical and numerical accuracy is necessary for routine engineering applications. In particular, the engineers require the most accurate results from the fastest core calculations possible to assess reactor design and safety, and this becomes possible only developing specialized models with a clearly delimited application domain [4].

The TH design is initially conducted at the fuel element level by means of DOCs based on the Sub-Channel (SC) method, such as ANTEO+ [5, 3] for undeformed bundles and EFIALTE for deformed bundles (the latter is currently under development within the H2020 PASCAL project). Moving to the full core analysis, a first approximation can be obtained by running different standalone ANTEO+ calculations for the assemblies composing the core. A more accurate calculation should account for the inter Sub-Assembly (SA) heat transfer by self-consistently solving the TH problem within each SA and within the InterWrapper (IW) region.

A literature review pointed out that the available codes for full-core TH analysis of LFRs seems either too expensive computationally for the design phase (COBRA-WC and NETFLOW) or too simplified (SE2-ANL) [1, 6, 8]. This motivates the development of a new DOC solving the whole-core TH problem.

A first step towards the development of a full core SC code was represented by TIFONE, a code for the IW flow and heat transfer, which has been recently developed and preliminary validated at ENEA Bologna within a contract with Politecnico di Torino [7].

The proposed work consists in the design, development and preliminary validation of a TH code based on the SC method for the full core analysis of an LFR.

The code design shall comply with specific requirements to be set at the beginning of the activity, and follow rigorous software quality assurance guidelines such as those in [2]. The design shall be thoroughly described in a Software Design and Implementation Document (SDID) describing the governing equations, solution methods, data flow diagrams and pseudocode. The code development shall be carried out using the most recent Fortran 2018 standard, and take advantage of modern programming practices, aiming at maximizing the code execution speed and overall performance.

Quarterly reports are requested to track the advancement and progress of the work.

Work plan

The proposed work plan is here presented:

- The first phase of the work will involve a literature review on the state of the art of TH analyses at both the fuel element and whole core level. In parallel, the candidate will also become familiar with the latest FORTRAN 2018 standard. At the same time, the *new*cleo supervisors will formalize a Software Requirements Specifications (SRS) document where measurable requirements and goals for the tool to be developed by the candidate are set.

- The following phase of the work will involve the physico-mathematical formulation of the full-core problem, clearly stating the adopted governing equations, their simplifications and the numerical methods adopted for the solution. The resulting document will represent the first part of the Software Design and Implementation Document (SDID).
- The detailed code design phase will then be carried out, associating the various expected functions to be carried out by the code with specific code elements. This phase shall be carried out targeting modularity and testability;
- The development and testing of a SC code for the single fuel element (possibly based on ANTEO+ / EFIALTE) will then be carried out. The code will be benchmarked against ANTEO+ / EFIALTE.
- The development and testing of a SC code for the IW flow and heat transfer (possibly based on TIFONE) will then be carried out. The code will be benchmarked against TIFONE.
- The IW flow and heat transfer code will then be coupled to the single fuel element code (calling N_{SC} instances of the latter). The resulting tool will be thoroughly tested.
- The whole-core code will then be validated against existing experimental data.

Applicant profile

Master of Science in Nuclear, Mechanical or Aerospace Engineering.
Fundamentals in Numerical Analysis, Computational Fluid Dynamics and Thermal-hydraulics.
Computer skills (already present or willing to learn): LaTeX, Fortran, Python.

References

[1] T. L. George, K. L. Basehore, and W. A. Prather. Cobra-wc model and predictions for afast-reactor natural-circulation transient. Technical report, Richland, WA, 1980.

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Da restituire compilata in lingua inglese, in formato word

Title: in English (max 100 characters)	Development of protective coatings on structural steels for Lead Fast Reactor (LFR) applications
Research Topic: Briefly describe the research (max 500 characters)	The corrosion of structural steels (316LN) by liquid lead is a challenge for designing LFRs. Protective coatings that resist lead corrosion are required. This study aims to qualify the most developed coating processes for nuclear codes (e.g. RCC-MRx). Aluminizing, welding overlay or thermal projection, and Zr or FeCrAl coating will be studied. Microstructural and mechanical characterization, as well as lead corrosion and irradiation experiments, will be conducted. The goal is to improve the design of LFRs.
Skills: Describe the skills and characteristics the candidate should have to develop the research topic (max 500 characters)	• Master degree or equivalent in Materials Science, Metallurgy, or electrochemistry • Knowledge and/or experience in testing mechanical properties of materials (tensile, creep, fatigue, toughness…) • Knowledge in phases equilibrium thermodynamics • Knowledge and/or experience in software relevant for materials science (python, matlab, thermocalc…) • Knowledge in corrosion is an advantage

Scholarship type	□ DM 117/2023

Scientific Responsible	Andrea, Barbensi, andrea.barbensi@newcleo.com

Da restituire compilata in lingua inglese, in formato word

Title: in English (max 100 characters)	Development and characterizations of structural steels welds for Lead Fast Reactor (LFR) applications

Research Topic: Briefly describe the research (max 500 characters)	Welding of structural steels is essential and often a critical issue in nuclear industry. In LFR, the challenge is to qualify welds: - Of common structural steels (316L(N)) in liquid lead - Of advanced structural steels (AFA steels) in liquid lead The main purpose of this study is to continue the welding developments made in the framework of European programs (such as GEMMA) and fill the gaps to bring them to qualification in nuclear codes for lead environment (RCC-MRx…). In particular, this includes: - Thermomechanical tests in air and lead (creep, fatigue…) - Processes studies (SAW, GTAW, EB…) - Filler material studies and qualification

Skills: Describe the skills and characteristics the candidate should have to develop the research topic (max 500 characters)	• Master degree or equivalent in Materials Science, Metallurgy, Mechanics or equivalent • Knowledge and/or experience in main laboratory characterization techniques • Knowledge and/or experience in testing mechanical properties of materials (tensile, creep, fatigue, toughness…) • Knowledge in welding processes and microstructure • Knowledge and/or experience in software relevant for materials science (python, matlab…) • Knowledge in corrosion is an advantage

Scholarship type	□ DM 117/2023

Scientific Responsible	Andrea, Barbensi, andrea.barbensi@newcleo.com

Da restituire compilata in lingua inglese, in formato word

Title: in English (max 100 characters)	Development of advanced structural materials resistant to liquid lead corrosion for Lead Fast Reactor (LFR) applications
Research Topic: Briefly describe the research (max 500 characters)	Alumina Form Austenitic (AFA) steels are very promising materials for LFR and other corrosion resistance applications. The main purpose of this study is to continue the AFA steels developments made in the framework of European programs (such as GEMMA) and fill the gaps to bring optimized grades to qualification in nuclear codes (RCC-MRx…). In particular, this includes: - Thermomechanical tests in air and lead (creep, fatigue…) - Manufacturing studies (tubes, powder metallurgy…) Thermodynamical and basic characterization campaigns are also in the scope to further optimize AFA grades or to explore other promising materials (High Mn steels, MAX phases…).
Skills: Describe the skills and characteristics the candidate should have to develop the research topic (max 500 characters)	• Master degree or equivalent in Materials Science, Metallurgy, or electrochemistry • Knowledge and/or experience in main laboratory characterization techniques • Knowledge and/or experience in testing mechanical properties of materials (tensile, creep, fatigue, toughness…) • Knowledge in phases equilibrium thermodynamics • Knowledge and/or experience in software relevant for materials science (python, matlab, thermocalc…) • Knowledge in corrosion is an advantage

Scholarship type	□ DM 117/2023

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Da restituire compilata in lingua inglese, in formato word

Title: in English (max 100 characters)	Development and characterization of coatings for corrosion protection of nuclear fuel claddings in Lead Fast Reactor (LFR) environment

Research Topic: Briefly describe the research (max 500 characters)	The corrosion of fuel cladding steels by liquid lead is a technological challenge for the development of LFRs. The solution under consideration consists of a protective coating deposited on the outer surface of the cladding tube. Various deposition processes (e.g., PLD, HiPIMS) and coating materials (e.g., Al_2O_3, FeCrAl) are being evaluated. This study aims to develop and qualify coatings for cladding corrosion protection in terms of key properties, e.g., adhesion during tube deformation and resistance to high temperature. Microstructural and mechanical characterization, as well as lead corrosion and irradiation experiments, will be conducted.

Skills: Describe the skills and characteristics the candidate should have to develop the research topic (max 500 characters)	• M.Sc. degree or equivalent in Nuclear Engineering, Materials Science, Metallurgy, or similar. • Preferably, a thesis work with connection to experimental characterization of materials (e.g., testing of mechanical properties, electron microscopy applications) or materials development. • Knowledge in corrosion and protection of materials would also be an asset.

Scholarship type	☐ DM 117/2023

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