SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Optimization and design procedure of a potassium Rankine cycle for Nuclear Electric Propulsion

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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1. Introduction

Current level of technologies have so far prevented men from venturing into that part of space that goes beyond the distance between the Earth and the Moon, usually referred to as deep space. The only human-made voyages have involved robotic spacecraft or space probes, with Voyager-1 being the farthest one men have ever produced. For a manned mission to become a reality, the first obstacle to overcome is the reduction of transit time, which implies a mitigation of health hazards for the crew. Up to now, chemical propulsion has been the most widely adopted solution but its effectiveness decreases as the flight distance grows. On the other hand, electricity from solar arrays, which play a key role in a number of applications such as station keeping on geostationary satellites, suffers from major drawbacks like a low power level and an efficiency that is inversely proportional to the square distance from the sun. Nuclear Electric Propulsion seems instead an attractive solution for deep space travel since the power provided to the thruster is not limited by fuel properties and a high specific impulse can be obtained. This implies a more efficient use of propellant, which in turn benefits the overall mass of the propulsion unit.

This work is part of a more extensive endeavor to evaluate different nuclear electric propulsion configurations to find the best one for each different mission requirement. To do that, an important figure of merit that is considered for every kind of engine is the specific mass, defined as the ratio between the system mass and the electric power produced. How the latter quantity varies with respect to different operative conditions in a conversion unit based on a Rankine cycle is investigated within this study. The positive effects of employing a liquid metal working fluid such as potassium and the benefits that a high power-density thermal source as a molten salt micro-reactor offers are presented and discussed.

2. Optimization procedure

To get the optimal power conversion configuration, every unit has to be studied in a coupled way, so relationships among each component of the cycle must be established. Thus, this work aims at creating a metamodel that finds connections between a set of input data and some objective outputs. The first step is then to build one or more databases that can include the largest possible number of design configurations. Different matrices of operative conditions, including both sides mass flow rate, inlet pressure and temperature etc. are created for a range of thermal powers. These values are used as inputs to perform thermo-physical calculations of the system through a Rankine cycle model developed and implemented in Modelica. The outcomes of each run simulation form a separate data set, which is later exploited by a Python interpolating algorithm to relate any design choice to explicit values of power produced, overall mass, and so on. After having translated the requirements of the reactor, the turbine and other units into numerical constraints, the target function to be minimized is processed by an optimization algorithm, which eventually yields the best combination of input variables. By proceeding in the same way and employing databases associated with different power levels, it is possible to figure out how a parameter such as the specific mass is affected by operative condition changes as well as the way each component influences its behavior.

3. Molten salt micro-reactor

The important role played by the mass of the spacecraft in any mission consideration forces finding the lightest possible solution for every component and the same goes for the nuclear reactor. The molten salt concept has some particular advantages from this point of view since it can boast an extremely energy-dense fuel and an almost total absence of internal structures. These features place it among the reactors with the highest core average power density. For these reasons and also thanks to their long experience in this field, researchers at the LPSC (*Laboratoire de Physique Subatomique et de Cosmologie*) of Grenoble decided a few years ago to design a molten salt fast micro-reactor for nuclear electric propulsion purposes. An eutectic salt based on LiF-UF_4 (molar composition 73.4% LiF and 26.6% UF_4) is circulated inside a spherical core coated by a double layer consisting of a TZM alloy cladding and a beryllium reflector. The latter is kept below 800 K to prevent it from serious swelling through a thermal insulation carbon foam. By opting for the low-enriched uranium (20% enriched uranium-235) fuel, an optimization to obtain the minimum core critical mass has been performed, resulting in the 1 MWth reactor core of 2497 kg shown in fig. 1 and summarized in table 1.

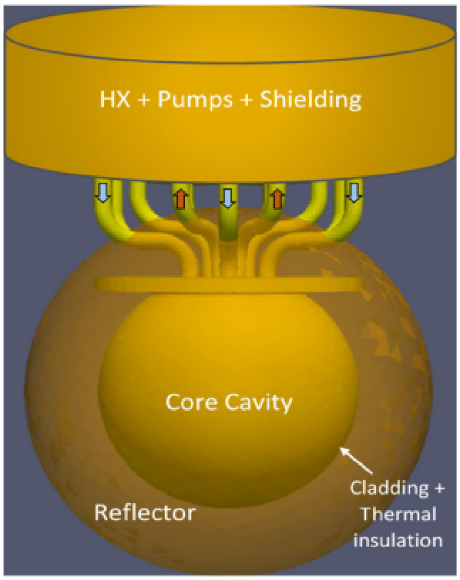

Figure 1: Layout rendering of the space MSR core with a fast spectrum [2].

To limit the reactivity swing to about 170 pcm over the 10 years of expected operative life, the addition of burnable poisons with a boron concentration of 0.07% is envisaged. Thanks also to its high fuel-temperature feedback coefficient (-3.8 pcm/K), it represents a system with no need for active reactivity control and is virtually maintenance-free. Although, in principle, PCS optimization can be applied to diverse reactor types, the LPSC molten salt reactor is adopted as a power source reference to define specific optimization constraints.

Core component masses	
Molten fuel salt (kg)	1003
Cladding (kg)	344
Reflector (kg)	1150

Table 1: Main MSR parameters [2].

4. Potassium Rankine cycle

Power conversion is a key aspect of any electric propulsion unit. From a thermodynamic point of view, it has nothing different with respect to terrestrial conversion systems and it also employs quite the same components. Both Rankine and Brayton cycle have been considered for high-power NEP since the 1960's but the reasons making the former a better candidate will be clear soon. In general, what makes these types of space systems so special is the working fluid. Liquid metals claim large thermal conductivity, small kinematic viscosity, small vapor pressure and a wide temperature range over which they remain in the liquid phase. Therefore, they are considered efficient heat transfer media in processes with limited heat exchange surfaces and exceptionally high thermal loads. Compared to other alkali metals, potassium proved a higher boiling stability and heat transfer capability as well as the lowest tendency of erosion on turbine blades. Moreover, the possibility to operate at high temperatures combined with a heat rejection process at constant saturation temperature significantly reduces the weight of the radiator, which is the most massive component of the system.

5. Modelica model

The optimization procedure starts with the collection of multiple combinations of output data, namely system power, component masses, etc., each of which is associated with a precise set of input values. All the required calculations are handled through a Modelica model that replicates the Rankine cycle configuration displayed in fig. 2.

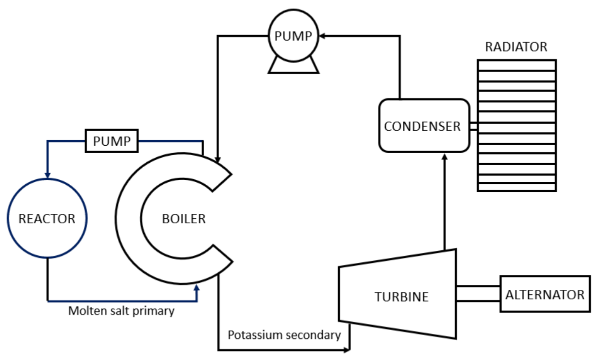

Figure 2: Rankine cycle schematic.

The latter is made up of an arc-shaped, counter-current, shell-and-tube boiler that produces dry vapor to be sent to a nine-stage axial flow turbine. A heat rejection system (HRS) developed at LPSC and formed by a series of heat pipes connected to radiator plates brings back the potassium to the liquid phase, which is eventually pumped back to repeat the cycle. In Modelica, all the very standard models present in code libraries, like the *ThermoPower* one, were adopted for each component except for the heat exchanger. In fact, due to the absence of a potassium medium model, a dedicated one was developed employing state equations and heat transfer correlations mostly obtained through interpolation of data from experiments carried out in the 60's. The heat transfer coefficient distribution that results from applying the model to an example 3.3 MWth counter-current boiler is displayed in fig. 3. To validate the outcome, the model was then exploited to predict the heat transfer coefficient distribution of boiler designs tested by several experimental facilities and discrepancies in the results of at most 10% were found [1].

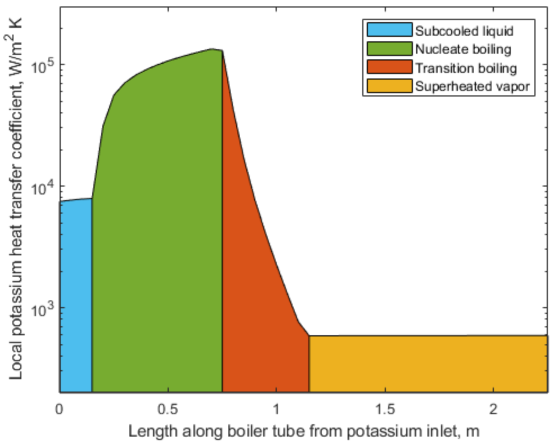

Figure 3: Typical heat transfer coefficient distribution implemented in Modelica.

Nonetheless, it is demonstrated that a higher accuracy level is not needed since the poor heat transfer capability of molten salt sizes the largest part of the boiler. Potassium contribution instead becomes relevant when vapor quality rises and tube walls are dried. To postpone the onset of transition boiling, the effectiveness of twisted tape insertions is proven, while the prospective of a rotating or cyclone boiler is promising but still needs to be investigated. The remaining PCS units are implemented in the model by following the specifics from the reference work of Oak Ridge [3] and an equation to estimate the mass of each component is included in the calculations.

6. Metamodel creation

Although the discussed optimization procedure could be applied to any objective quantity, the need for a power conversion system as light and compact as possible forces the attention to the mass as the prominent parameter. In particular, the specific mass (kg/kWe), defined as the ratio between the overall PCS mass and the electric power produced by the generator, allows a comparison between different designs. However, Modelica is not intended to directly optimize a system and thus it is not possible to fix a desired power level and expect the tool to accord all the other variables. To do that, the proposed solution is the creation of a metamodel. Commonly conceived as a simplified version of another model, the latter is nothing but an abstraction of those theoretical equations or empirical laws used to describe phenomena in the real world.

6.1. Variables identification

In general, the metamodeling process involves identifying relations or properties between the components, namely the outputs and inputs of a model, and expressing them through algorithms. The inputs do not necessarily include all the variables and parameters that define the main model but only those influencing the output quantity to be optimized. In this sense, mass flow rate and inlet temperatures on both sides, secondary side pressure and boiler heat transfer area are the variables chosen to form a matrix of Rankine cycle configurations. By setting to 50 K the maximum temperature difference that the primary side molten salt can undergo, value intervals for the variables mentioned above are defined for the following thermal power levels: 60 kW, 120 kW, 250 kW, 1 MW and 2 MW. Each of these input databases is used to run multiple simulations in Modelica by considering, for sake of simplicity, the parameters reported in table 2 as constants.

Parameter	Value
Turbine Speed [rpm]	55,000
Mechanical efficiency [%]	100
Isentropic efficiency [%]	100
Boiler Material	Nb-1%Zr
Density [kg/m^3]	8,590
Thermal conductivity [W/(mK)]	50
Primary side pressure [bar]	1
Tube thickness [mm]	0.8
Shell thickness [mm]	1.2

Table 2: List of constant parameters in the Rankine cycle.

6.2. Optimization and constraints

Once thermodynamic calculations have been performed for every design configuration, a functional dependence is sought between the input variables and any output quantity of interest. This goal is achieved in this thesis by exploiting the open-source Python software named *SciPy* and its piecewise multi-variable linear interpolator, which triangulates input data and performs linear barycentric interpolation on each triangle. In this way, it is identified not only the function to optimize (i.e., the specific mass) but also constraint functions that allow to add requirements for the optimal conversion system to fulfill. The equations thus obtained are processed by the *Sequential Least SQuares Programming Algorithm* (SLSQP), a minimization method implemented once again inside the *SciPy* framework, by demanding a certain power level, 100% quality at the boiler exit and a moisture level in the turbine below 15%. In the end, the algorithm provides a combination of variables yielding the lowest cycle-specific mass; however, this value is just the minimum closer to the set of starting points, also called seeds, assigned to the optimizator. To get a more accurate estimation, the same procedure is performed multiple times with different seeds and just afterwards the best design configuration is chosen. A diagram summarizing the whole procedure is presented in fig. 4.

7. Results

Terminated all the optimization processes, the outcome configurations are interpolated in order to identify useful trends. In particular, the comparison carried out in fig. 5 shows the different contributions to the specific mass of each component when the inlet temperature of the primary fluid is set to 1200 K. As expected, the relative importance of every sub-system progressively reduces, except for the heat rejection system. This behavior was therefore deepened

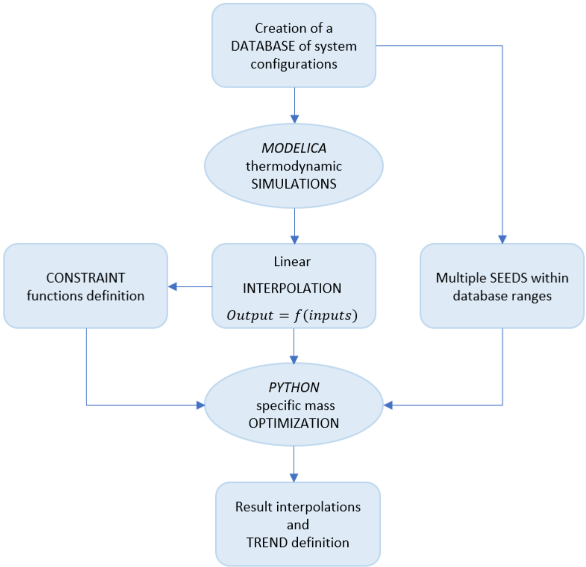

Figure 4: Diagram of the metamodeling and optimization procedure.

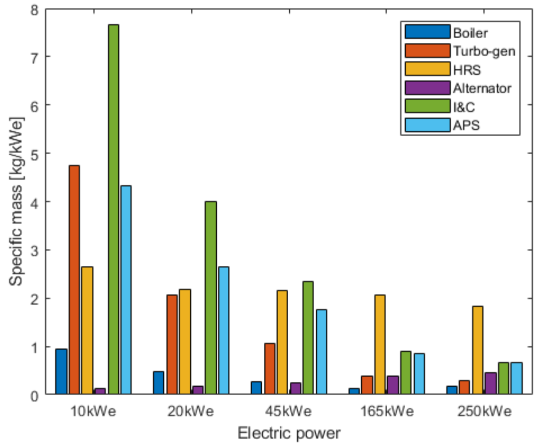

Figure 5: Contribution to the power conversion system specific mass by each component with a primary side inlet temperature of 1200 K.

through a dedicated analysis, which confirmed that the main variable influencing the radiator mass is the molten salt inlet temperature. In fact, for every power level investigated, an increase in temperature on the primary side of 100 K allows a savings of about half the unit mass thanks to a higher temperature of condensation. However, at high power, this mass reduction is obtained only at the expense of dramatically reducing the cycle efficiency. This limit clearly reflects also on the system specific mass behavior. Although the beneficial impact of a higher hot temperature is visible, the steep decrease in specific mass that interests relatively low-power systems becomes almost flat when the 100 kWe power threshold is overcome. This demonstrates the existence of a limit to any space Rankine cycle mass optimization, which is established by the adopted heat rejection system.
A successive study is done by applying the optimization procedure to example power conversion systems. To do that, the molten salt reactor is supposed to be operated at its nominal power level of 1 MWth which ensures a core outlet fuel temperature of about 1,200 K. To allow a more comprehensive evaluation of the whole propulsion unit, also the masses of molten fuel, reactor core cladding and reflector reported in table 1 are taken into account, as well as the power management and distribution system, which has been so far neglected. Moreover, the efficiency values suggested by ORNL for either the turbine and the alternator, respectively of 74% and 0.88%, are adopted. The resulting optimized configuration specifics are listed in table 3 whereas a summary of the estimated masses is presented in fig. 6. An overall system mass of 3862 kg is predicted for a 110 kWe system, which corresponds to a PCS specific mass of 8.06 kg/kWe and an overall system one of 35.1 kg/kWe.

Variable	Value
Thermal power	1 MW
Electric output	110 KWe
Primary side flow rate	24.02 kg/s
Secondary side flow rate	0.48 kg/s
Secondary side inlet temperature	948 K
Secondary side inlet pressure	2.86 bar

Table 3: 110 kWe potassium Rankine cycle system specifics obtained through the optimization procedure.

The same procedure is then followed with equal consideration but requiring the highest possible cycle efficiency. A 150 kWe system of 4657 kg with an efficiency of 15% and a PCS specific mass of 8.58 kg/Kwe and a system one of 31.0 kg/KWe is obtained. This result remarks the importance of a coupled analysis. In fact, it is demonstrated that the power conversion system with the lowest specific mass is not necessarily the optimal solution for the overall propulsion unit. The reactor and the radiators in particular are strictly related and once again a trade-off study between mass and efficiency is crucial to design the best system.

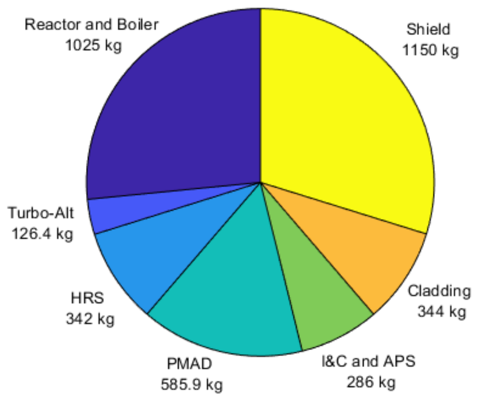

Figure 6: Major components estimated masses for a 110 kWe potassium Rankine nuclear reactor power system.

8. Conclusions and future developments

This work advanced the development of a code that could outline the steps for the design of any nuclear electric propulsion system. This kind of complex problem prevents treating each branch as a separate entity and interconnections must be identified and managed properly. Among the different components, a strong relationship is established between the nuclear reactor and the power conversion system. A Rankine cycle working with a liquid metal like potassium is confirmed as an attractive option thanks to the possibility of operating at extremely high temperatures, which also assist in rejecting heat more efficiently. On the other hand, a molten salt reactor appears to be one of the leading candidates among the several reactor concepts because of its many inherent qualities. Functional relationships between these two systems were effectively established by means of a meta-model incorporating a large set of different operating conditions. This was made possible by a specifically developed and validated Modelica heat transfer model for potassium flow. However, no evidence of the effects that zero gravity could produce on boiling is available and so future research should focus more on that as well as on how mechanical stresses, pressure loads and corrosion issues could impact the design of components such as turbines and heat exchangers. In conclusion, this work stressed the importance of a more comprehensive analysis that accounts not only for the mass of the system but also for its efficiency. The gap between two of the several components of a propulsion unit was bridged, but much remains to get the job done.

References

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