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Exploration of a Fast Pathway to Nuclear Fusion: Thermal Analysis and Cooling Design Considerations for the ARC Reactor

Exploration of a fast pathway to nuclear fusion: thermal analysis and cooling design considerations for the ARC reactor

S. Segantin[1*], R. Testoni[1], Z. Hartwig[2], D. Whyte[2], M. Zucchetti[1,2]

[1]Dipartimento Energia, Politecnico di Torino, Italy
[2]Plasma Science and Fusion Center, MIT, Cambridge (MA), USA

Progress in technological fields such as high temperature superconductors, additive manufacturing and innovative materials has led to new scenarios and to a second generation of Fusion Reactors designs. A new Affordable Robust Compact (ARC) Fusion Reactor, which meets its goal in a cheaper, smaller but even more powerful, faster way to achieve Fusion Energy, has been designed by MIT. In order to define ARC's role in future electricity grids, a feasibility investigation of the load-following concept has been carried out, starting on ARC's most close to plasma component, the vessel. Finite elements analysis models have been designed and thermo-mechanical analysis have been conducted. In this framework thermal fatigue and creep remain the main issues. The present study identifies and verifies a suitable temperature range for the vacuum vessel coolant. Indeed it is found to satisfy both requirements for structural material's lifetime and thermodynamic efficiency optimization.

Keywords: ARC, tokamak, thermal analysis, load-following capability, COMSOL

I. Introduction

Affordable Robust Compact (ARC) is a tokamak concept that is in design phase at the Plasma Science and Fusion Center (PSFC) of MIT [1] (Figure 1). It is believed to be one of the most likely tokamak to be the first generation of fusion reactor connected to electricity grids around the globe. Thank to high temperature superconductors it will be way smaller, faster and cheaper to build and maintain than other main designs.

Fusion is predicted to replace fossil fuels and nuclear fission's role in future grids [2,3]. The mentioned sources are well known to represent the baseload of every electric grid in the world, as they are the only ones able to provide power in any possible situation. Unlike renewables, which depend on several external conditions, such as plant geographical position and weather for instance, fossil fuels and fission rely just on fuel supply and plant integrity to produce energy. Moreover, because of plant's efficiency limits and physics related issues or risks, some fossil fuel plants and nuclear fission, especially, are very static in the amount of power output.

Nuclear fusion is theoretically able to change its power output quickly and in safety. It is therefore possible to investigate the feasibility of a load-following power plant based on ARC reactor, able to change power output any time the grid requires more electricity for users [3]. The beginning of this study focuses on ARC's closest component to the power source, which is the vacuum vessel, which contains the plasma. Indeed, plasma is the main heath source, providing loads to the vessel, divertors and also directly in the blanket, because of radiation and neutron effects. Vessel's coolant, and energy carrier fluid, is a Lithium Fluoride and Beryllium Fluoride molten salt (2LiF-BeF$_2$ or FLiBe), chosen for its blanket properties [1] and good activation predictions [4]. While vessel and divertor's main structure has been chosen to be made of Inconel 718 with a tungsten first wall.

This work has been developed in this framework. In particular, a FLiBe working range temperature has been designed and optimized to guarantee the plant's thermodynamic efficiency and a satisfying main vacuum chamber's lifetime. The idea is that, as the power output required changes, the cooling system adapts the plant to the new plasma power, for each power value reachable by ARC. More specifically, FLiBe has to adapt its flow rate and temperature range, meant as inlet-to-outlet temperature in the vessel, to each plasma power reached. This can be done by implementing dynamic pumps, able to modify the flow rate, and heat exchangers able to change their heat removal capacity (e.g. changing the number of pipes and length of FLiBe path in the exchangers by means of valves). Thus, modifying the flow rate it is possible to change the heat removal capacity in the vessel, and variating temperatures it is possible to protect the chamber from avoidable stress peaks and thermal stress cycles that cause fatigue. For instance, if the electric grid asks for more power, plasma increases its power. Moreover, coolant's flow rate increases in order to remove more power and also to satisfy the temperature range set to prevent vessel damage caused by thermal stress.
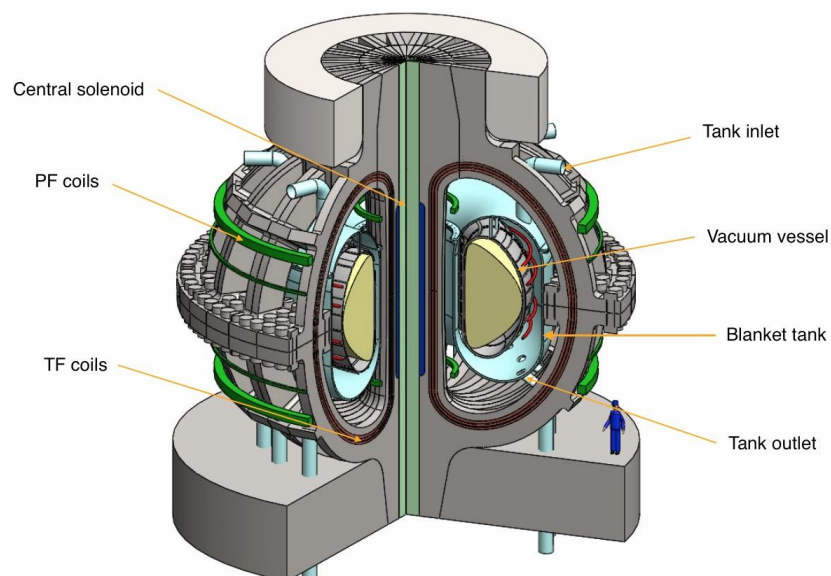

Fig. 1. Affordable Robust Compact (ARC) tokamak [1].

II. Model description

II.A. FLiBe temperature range

ARC's vacuum vessel is a double walled, toroidal shaped chamber made of several layers: a 1 mm first wall made of Tungsten, follows a 5 mm layer of Inconel 718 for structure of the inner wall. Inconel is cooled by 20 mm wide FLiBe channels. Behind the channels, 10 mm of Beryllium multiply neutrons for improving the TBR and it is sustained by 30 mm of Inconel 718 [1], which is, once again, the structural material for the outer wall. The whole component lies in a tank full of FLiBe, which is a molten salt, made from a mixture of Lithium fluoride and Beryllium fluoride [5].

The vacuum chamber is heated up by electromagnetic radiations incident on the first wall and by neutrons escaping the plasma and reaching the blanket tank all the way through the vessel's layers. The coolant has three main different inlets: the first goes in the walls of the vessel, circulating poloidally from the top to the bottom of the chamber, the second flows in the divertors and the third is an auxiliary flow that enters directly in the tank and that is not necessarily always used. All the flow rates converge in the tank once they covered their path through the chamber and divertors, and the tank is the last reactor's component that gathers the coolant and then sends it to the heat exchangers, as it can be seen in Fig.2.

Once the material configuration was designed, it has been possible to model loads and sinks. A surface thermal load models radiative heating for the plasma facing material, while neutron energy deposition has been modeled as a volumetric heat source. More specifically, the multiple neutron effects that cause energy deposition and gamma radiation emission, such as scattering, absorption (n, γ), multiplication $(n,2n)$, tritium breeding from lithium-6 (n, T) etc., have been tallied and evaluated by the MCNP model described in [6] and subsequently modeled as heat loads for FEM simulation. Finally, last modeled effect was the FLiBe coolant, which could be seen as a turbulent film with variable temperature.
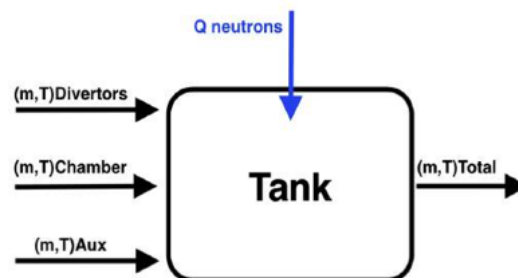

Fig. 2. Scheme of bulk tank's loads, sinks and flow rates.

Recalling the load-following concept, ARC reactor is able to change its power output. There is therefore a range of fusion power in which ARC's plasma can stand during a normal working day, with a peak of 1GW. Thus, it has been decided to change FLiBe's inlet and outlet temperatures in the vessel, for each power value that ARC could experience during the day. Operation made possible by playing with coolant pump's flow rate and the heat sinks. The goal is to safeguard vessel's creep and thermal fatigue lifetime, which basically decreases as component's temperature increases.

Two boundaries for FLiBe's temperature were set up. The lower one, experienced in the vessel's inlet is FLiBe's melting point, which is around 730 K [5,7]. The upper limit is due to structural material: Inconel 718 experiences a drop in mechanical resistance to creep above roughly 930 K [8,9]. Thus, using the heat exchange equation (1), where Q is the estimated heat load [W], U is the global heat transfer coefficient [W/(K · m²)] and A is the exchange surface [m²], it has been possible to come up to the highest FLiBe's temperature allowed in the vessel's region, for each fusion power reached by plasma.

$$Q = U * A * \Delta T \qquad (1)$$

It is important to remark that the upper limit was the Inconel temperature limit in $\Delta T = T_{Inconel} - T_{FLiBe}$. In particular, it has been chosen to look at the inner Inconel layer, as it is the most stressed and the less prone to further design modifications, with respect the outer wall, leaving outer vessel's layer evaluations to a finite elements model. Then, the variable to look for was the FLiBe temperature in the hottest part of the channels, namely outlets.

Finally, the energy conservation equation (2) was applied to come up to the last FLiBe temperature of the system under study, namely the tank's outlet one.

$$Q_{neutrons} + \left(\dot{m}c_pT\right)_{outVessel} + \left(\dot{m}c_pT\right)_{outDivertors} + \left(\dot{m}c_pT\right)_{outFlow} - \left(\dot{m}c_pT\right)_{outTank} = \frac{\partial E}{\partial t} \qquad (2)$$

where $Q_{neutrons}$ is the neutron power deposition in the tank [W/m³], m is the flow rate [kg/s], c_p is FLiBe's specific heat capacity [J/kg/K], $\partial E/\partial t$ is the system's energy change rate [J/s] and T is the fluid's temperature [K], taking into account all FLiBe paths in the machine. More specifically the main vessel and the two divertors have dedicated FLiBe inlet for the heat removal in the structure, while they all have the outlet directly in the tank, where coolant's keep being heated by neutrons and radiations.

Fig. 3 shows the final temperature range designed. $T_{InIdeal}$ is the minimum FLiBe temperature allowed, it gives a gap of ~20 K above freezing temperature, $T_{718Limit}$ is the inner wall temperature limit to creep, T_{InVV} and T_{OutVV} are vessel's

inlet and outlet temperature respectively and $T_{OutTank}$ is tank's outlet temperature. Vessel's inlet temperature stands always above 750K that gives a 20K gap above FLiBe's freezing temperature. Playing with pump's flow rate it has been possible to set the maximum vessel's outlet temperature (purple) allowed by Inconel's limit. As neutrons flux also reaches the bulk tank, the coolant keeps being heated up until it leaves the blanket tank (orange). It is possible to notice that as power increases, in order to maintain Inconel's temperature almost constant, it has been necessary to decrease FLiBe's outlet temperature.
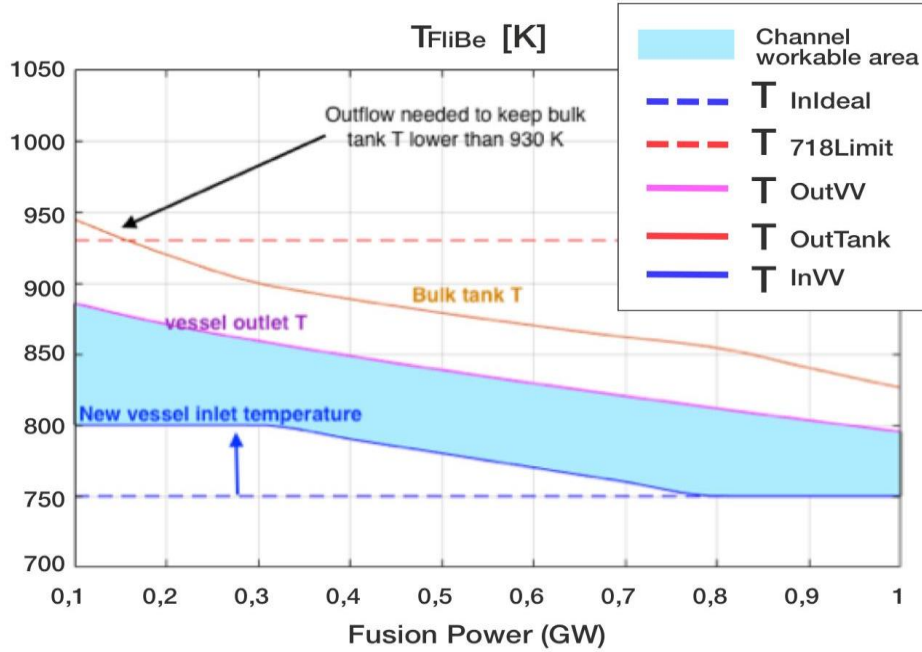

Fig. 3. FLiBe's temperatures [K] of vessel inlet, outlet and bulk tank vs fusion power [GW].

II.B. Finite elements model

In order to validate the designed temperature range and to carry out the creep and thermal fatigue lifetime prediction, a finite element analysis has been conducted out on the vessel's main chamber.

In Table I, the main material properties equations, implemented in the model for Inconel 718, tungsten and beryllium, are shown [10, 11]. The reported thermo-mechanical properties are thermal conductivity (k), coefficient of thermal expansion (CTE), specific heat capacity (c), and Young modulus (E). Electromagnetic radiation and neutron's effects have been modeled as thermal loads, as anticipated in section II.A.

Table I: Main thermo-mechanical properties of Inconel 718, tungsten and beryllium Refs. [10, 11].

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			Inconel 718
	k	$\frac{W}{m*K}$	3.495867+2.673305E-2*T-1.11803E-5*T^2+3.606836E-9*T^3+8.235547E-14*T^4
	CTE	$\frac{\mu m}{m*K}$	2.057392E-6+5.935004E-8*T-9.860805E-11*T^2+5.80522E-14*T^3
	c	$\frac{J}{kg*K}$	361.3373+0.2378248*T+7.560689E-6*T^2
	E	Pa	2.216171E11-1.071145E8*T+118609.2*T^2-77.87834*T^3
			Tungsten
	k	$\frac{W}{m*K}$	240.51-0.2899*T+2.5403E-4*T^2-1.0263E-7*T^3+1.5238E-11*T^4
	CTE	$\frac{\mu m}{m*K}$	5.0777+5.6862E-4*T
	c	$\frac{J}{kg*K}$	116.37+7.1119E-2*T-6.5828E-5*T^2+3.2396E-8*T^3-5.4523E-12*T^4
	E	Pa	413.3-7.8396E-3*T-3.6582E-5*T^2+5.4849E-9*T^3
			Beryllium
	k	$\frac{W}{m*K}$	430.35-1.1634E-3*T^2-1.0097E-6*T^3+2.3642E-10*T^4
	CTE	$\frac{\mu m}{m*K}$	8.4305+1.1464E-2*T-2.9752E-6*T^2
	c	$\frac{J}{kg*K}$	606.91+5.3382*T-4.1726E-3*T^2+1.2723E-6*T^3
	E	Pa	313.53-5.643E-2*T

In particular, it has been taken into account that neutron's load do not have a constant behavior in poloidal direction and that electromagnetic radiations, that deposit thermal power on the first wall do not increase linearly with plasma power, because of Bremsstrahlung [12].

FLiBe's effects have been modeled as convective film with a turbulent behavior and variable temperature, according to above described computations. More specifically, for each power value, FLiBe's temperature computed using equation (1) has been set as coolant's temperature in the channels. Knowing that, in order to guarantee the designed vessel's inlet-to-outlet ΔT (Fig.3), it is possible to adjust the mass flow rate.

Bulk tank FLiBe has been modeled as a convective film with a low turbulence. Film's temperature has been set according to equation (2) results, which are dependent on the fusion power and mass flow rate given by equation (1). This model is a conservative assumption, as equation (2) gives the highest temperature reached by FLiBe in its entire loop and should be seen in the bottom of the tank, near its outlet, rather than around the whole vessel.

Loads, which are shown in table II, have been applied to both a toroidal symmetric 2-D model and a 3-D model with same type of loads, material properties and configuration showing analogous results [3].

Table II: Main loads and boundary conditions used for the simulations [3].

Loads & B.C.	Heat exchange module
Toroidal symmetry	Yes
First wall load [MW/m^2]	0,5 @500 MWth
Neutron flux [MW/m^3]	Depending on material (16,5 for inconel's inner wall)
FliBe T [K]	Depending on fusion power
Channel convective coeff [W/K/m^2]	50000
Tank convective coeff [W/m^2/K]	5000

The model has been built using COMSOL software [10]. This tool is capable of running simulations on extremely complex components that the user can import from external 3-D CAD softwares and it is also able to deal with several physics modules (for instance the heat exchange module, the CDF module and the structural module) coupling their interactions.

Finally, for the mesh it has been chosen to set the COMSOL default element geometry (i.e. "free triangular" for the 2-D axisymmetric model) but with a very refined lattice, in order to get the mesh quality very close to the unity ("extra-fine" element size has been considered sufficient for the purpose).

III. Results and discussion

Here, main results of the finite elements analysis are shown and discussed. Numerical solutions by means of the COMSOL software tool have been considered more reliable than the preliminary computations, since it was possible to estimate the change of material properties with component's temperature.

An example of the graphic FEM (Finite Elements Method) output is shown in Fig. 4. The layer between the two walls can be easily seen (red), as it is at around 800 K. It can also be noticed that the upper side of the vessel is at a lower temperature than the lower side. This because in the top side there is the FLiBe inlet, the liquid flows from the top to the bottom extracting heat and raising its own temperature and vessel's one as well.

For each fusion power value temperatures of the structure layers have been measured and plotted in Fig. 5.
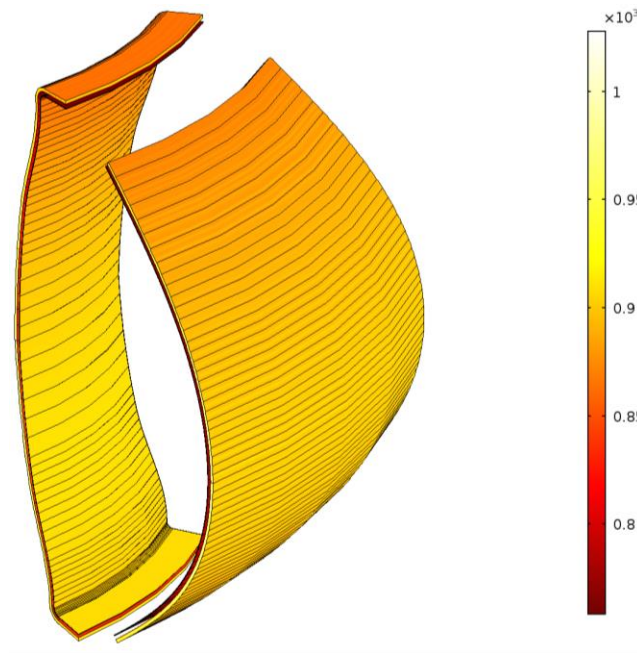
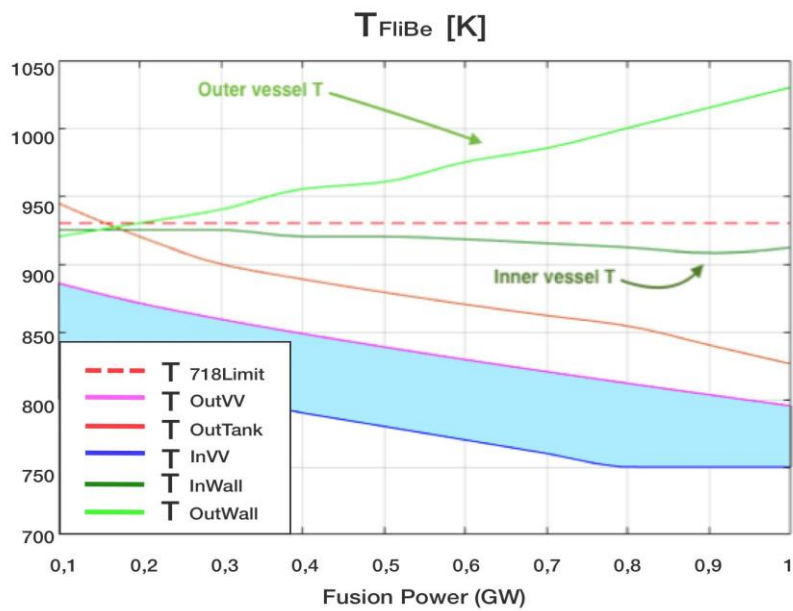Fig. 4. Vessel's temperature [K] at 1GW of fusion power.

Fig. 5. FLiBe's inlet (blue) and outlet (purple) temperatures in the vessel, FLiBe outlet temperature (orange) from the tank.

Vessel's inner (green) and outer (light green) temperatures.

From the graph it is possible to notice that vessel's inner wall results effectively cooled down. It is an expected result as coolant's temperature range has been designed keeping inner wall's temperature as threshold reference. On the other hand, the outer wall reaches relatively high temperature. The reason of the high temperature is that, like the whole vessel, it is subjected to very high neutron fluxes but, unlike other regions of the vessel, it is very thick, as it is designed

to bear most of structural stresses, and therefore, it is not adequately cooled down by FLiBe. However, it is not believed to be a concerning issue, as it is still far from Inconel's melting point and, especially, there is no particular constraint for its re-design.

Indeed, there are several solutions for this problem. A new configuration implementing a thinner outer wall has been modeled. Several simulations have been run systematically reducing the wall's in order to get down to the upper temperature threshold of 930 K without loosing too much structure stress-resistance (here assumed as structure thickness). This solution, which has been found to be optimal at 23 mm of thickness, causes neutron energy deposition to decrease and FLiBe cooling action to be more effective. The optimal solution is shown in Fig. 6. 2-D model with analogous materials, loads and sinks depicted for Fig.4 model is shown. On the upper part, it is in contact with FLiBe flowing in the channels at roughly 800K according to Fig.5, on the bottom side bulk FLiBe cools down it from the tank.
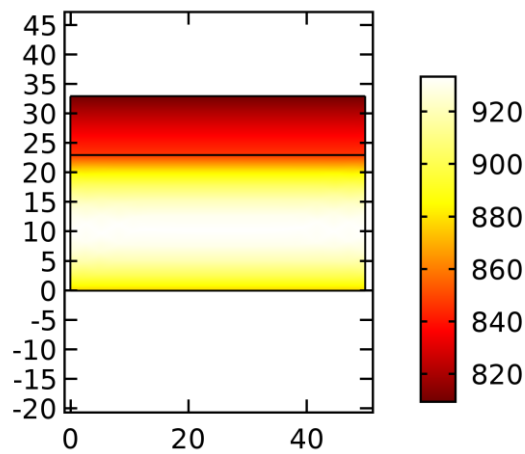

Fig. 6. Temperature [K] of a small portion of the vessel's outer wall at 1 GW, shrink solution.

An even more effective solution would be to increase distance between inner and outer wall. The latter one would be better shielded by neutrons without loosing robustness as structure. However this solution needs further neutronics modeling and studies, in order to get perfectioned [3, 12].

In order to conclude the coolant's temperature range design, other main plant parameters have been computed. In Fig. 7 FLiBe's inlet speeds required for each fusion power value are plot. The graph shows that velocities are in a feasible range for normal pumps and a heat exchanger as the vessel ultimately is.
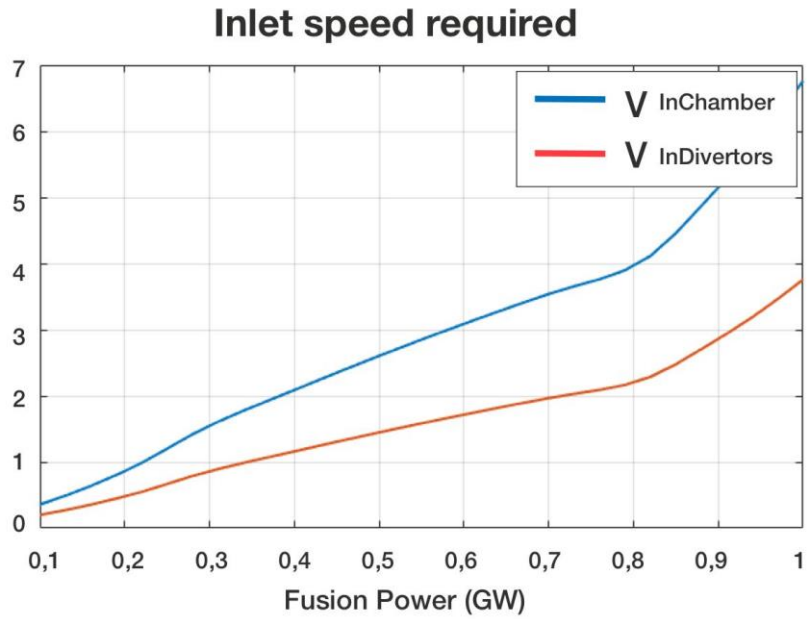
Fig. 7. FLiBe inlet speed required [m/s] for both Vacuum Vessel and Divertors vs Plasma Fusion power [GW].

The corresponding pumps' power is shown in Fig. 8. Power required by pumps is necessary in order to verify that it is a little fraction of the tokamak total electric power output, which is derived from the plant thermodynamic efficiency and the plasma power.
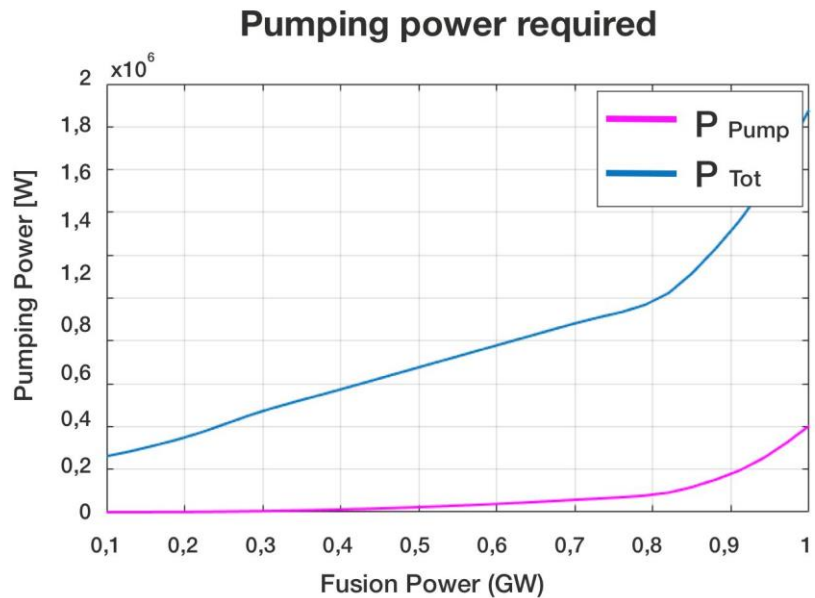

Fig. 8. Power required by pumps [$W*10^6$] for Vacuum Vessel and for the total tokamak vs Plasma Fusion power [GW].

Plant's efficiency has been calculated by equation (3) [13] and it is illustrated in Fig. 9.

$$\eta_{th} = 1 - \left(\frac{T_{amb}}{T_{out}}\right)^{1/2} \tag{3}$$

In equation (3) T_{amb} [K] is environment temperature while T_{out} [K] is the highest temperature in FLiBe loop, namely the tank's outlet one.
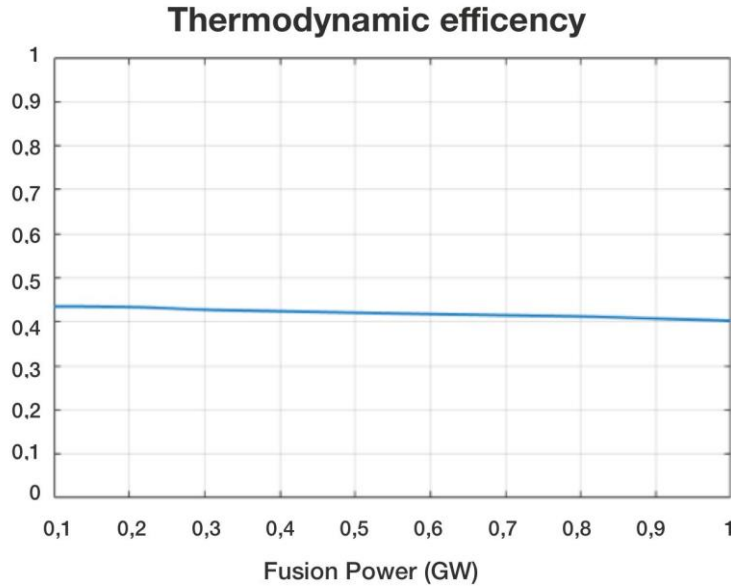

Fig. 9. Thermodynamic efficiency of ARC's power plant vs fusion power [GW].

Coolant's temperatures are relatively high in the whole power range, namely the difference between two T_{out} of different power is quite little compared to the difference of any T_{out} to T_{amb}. In addition to this, the temperature ratio in Eq. (3) is under the square route. These aspects give the efficiency an almost flat behavior in the tokamak's power range, which appears ideal for a load-following power plant.

Moreover, in Fig. 8 it is possible to see that the maximum power required by FLiBe pumps is roughly 2 MW corresponding to the 1 GW fusion power. According to Fig. 9, thermodynamic efficiency at 1 GW is about 0.39 giving a value of 390 MWe as plant's total output. Hence, at the point where pumps are most expensive in terms of power, (namely 1 GW of fusion power, 390 MWe of power output and 2 MW of pumping power) they ask for about 0.5% of total electric power output. Meaning that in the whole ARC power range, pumps play a negligible role in the plant's efficiency.

IV. Conclusion

ARC's vacuum vessel is strongly subjected to heath loads and neutron fluxes that are supposed to change in time in order to cover daily peaks of electricity requests. Following these premises, it is necessary to deeply design and study best conditions to achieve chamber's longest lifetime possible. As far as thermo-mechanical analysis is concerned,

creep and thermal fatigue are the most concerning issues, that have to be handled by adequately cooling down the component without undermine plant's efficiency.

This study tackles the abovementioned problems. It has been identified a structure temperature limit that avoids material's thermo-mechanical properties degradation. In order to avoid creep and thermal fatigue problems, coolant temperature have been chosen to keep structure under 930 K. Nonetheless, in order to get the maximum efficiency, temperature has been kept as close as possible to that threshold, since, the hottest the coolant, the highest the efficiency. Furthermore, FLiBe's temperature range has been designed for each fusion power most likely achievable by ARC's plasma.

Once the coolant temperatures have been identified, several FEM simulations have been conducted. The analysis have suggested that while inner wall is well cooled, the outer one should be optimized. The easiest solution is to thin the wall and it has already been implemented. However, a thicker wall would be better for structure resistance. Therefore, increasing the distance of the outer wall from the plasma, would be preferred, which is why future works are aimed to find the best FLiBe channels width in order to shield vessel outer wall from neutrons and optimize tritium breeding ratio as well.

As the coolant's optimized temperatures have been identified, it has been possible to compute the thermodynamic efficiency of the whole power plant. The efficiency, which is around 0.4, has been found to show a nearly constant behavior all the way through the entire power range allowed by ARC. This is believed to be an ideal efficiency behavior for a load-following power plant, seeing as how it will be required to change its power output relatively frequently.

Moreover, knowing FLiBe's properties it has been possible to compute pump's power required in order to compare it with the plant's power output and verify that it is negligible for each plasma power.

In conclusion, having found and verified a suitable coolant's range for ARC's vacuum vessel and blanket, it is possible to go ahead and investigate the vessel's lifetime under the assumption of load-following behavior, that is plasma changing its fusion power output almost cyclically every day.

References

[1] B. N. Sorbom et al., "ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets" , Fusion Engineering and Design, 100 (2015) **378-405**.

[2] J. P. Freidberg, "Plasma physics and fusion energy" , Cambridge university press, Cambridge MA, U.S., 2008.

[3] S. Segantin et al., "The lifetime determination of ARC reactor as a load-following plant in the energy framework" , Energy Policy, 126 (2019) **66-75**.

[4] B. Bocci, "ARC reactor: Activation analysis of the liquid blanket and structural materials for the vacuum vessel", Master thesis at Politecnico di Torino, April 2018.

[5] R. Serrano-López et al., "Molten salts database for energy applications", Chemical Engineering and Processing: Process Intensification, 73 (2013) **87-102**.

[6] Kuang, A. Q., et al. "Conceptual design study for heat exhaust management in the ARC fusion pilot plant." *Fusion Engineering and Design* 137 (2018): 221-242.

[7] M.S. Sohal et al., "Engineering database of liquid salt thermophysical and thermochemical properties", Idaho National Laboratory, Idaho Falls, 2010.

[8] C.C. Bast and L. Boyce, "Probabilistic material strength degradation model for Inconel 718 components subjected to high temperature, high-cycle and low-cycle mechanical fatigue, creep and thermal fatigue effects", NASA, Lewis Research Center, Cleveland OH, U.S. (1995).

[9] J. L. Ding et al., "Creep and creep rupture of an advanced silicon nitride ceramic", Journal of the American Ceramic Society, 77(4) (1994) **867-874**.

[10] COMSOL Multiphysics® www.comsol.com. COMSOL AB, Stockholm, Sweden. (last view: 3/20)

[11] ARIES team, "Thermal and Structural Properties of Fusion related Materials", http://aries.ucsd.edu/LIB/PROPS/PANOS/matintro.html, UCSD, San Diego, CA US. (last view 3/20)

[12] M. Zucchetti et al., "Exploration of a fast pathway to nuclear fusion: first thermomechanical considerations for the ARC reactor", Feb-Fresnius Environmental Bulletin (2019): 993.

[13] H. S. Leff, "Thermal efficiency at maximum work output: New results for old heat engines", American Journal of Physics, 55(7) (1987) **602-610**.