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Article

A Dual Coolant Lead-Lithium Breeder Blanket for a Fusion Power Plant Systems Model

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Abstract: (1) Background: The selection of apposite technologies for EU DEMO sub-systems is essential. The breeding blanket is a particularly critical sub-system since blanket design choices effect the entire fusion power plant (and plant site) design. (2) Methods: PROCESS is a well-established reactor systems code used to evaluate the viability of fusion power plant designs. PROCESS can be used to find a set of self-consistent parameters, allowing plant design optimisation within a given set of constraints. We have build a new Dual Coolant Lead-Lithium (DCLL) blanket model for PROCESS. (3) Results: We present the first results of implementing the DCLL model using DEMO Power Plant specifications. We find that using Flow Channel Inserts (FCIs) is necessary for all variations of the DCLL tested, in order to achieve a feasible plant design with our selected constraints. The modelled results agree that a DCLL blanket could potentially thermohydraulically outperform other blanket designs, specifically a Helium Cooled Pebble Bed (HCPB) blanket, depending on the specifics of the first wall and blanket design choices.

Keywords: DEMO; Breeding Blanket; DCLL; Systems Modelling; Power Plant Design

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1. Introduction

EU DEMOnstration Fusion Power Plant (EU DEMO) is a key step in the progress towards future fusion power plants. DEMO aims to demonstrate the production of hundreds of MW of net electrical power, that it is possible to operate a fusion reactor with a closed tritium fuel cycle, and that the plant can be operated with sufficient availability [1]. Breeding Blankets (BBs) are a critical plant component, responsible for tritium breeding, absorption of nuclear energy and a proportion of shielding, for which numerous different designs have been proposed and investigated. Selecting a BB design is complex, each concept will have different advantages and disadvantages with regard to factors such as thermal efficiency, design simplicity, tritium breeding capability, cost and safety. BB design choices also have significant effects on other plant systems that are not always simple to predict.

In this study, we implement Dual-Coolant Lead Lithium (DCLL) blanket model (an advanced blanket concept) for an EU DEMO type reactor in PROCESS [2] - an established power plant systems code designed to investigate the industrial viability of fusion power plant design choices. We explore the effects of changing key blanket parameters and compare our results to the DEMO Helium Cooled-Pebble Bed (HCPB) blanket model (a more technologically mature "starter" blanket candidate for DEMO).

A key advantage of the DCLL BB is that it is potentially more thermally efficient than other blanket types [e.g., 3,4]. In this study, we investigate the effect of using different PbLi coolant/breeder inlet and outlet temperatures, Multi-Module Segment (MMS) versus Single Module Segment (SMS) blanket design [5], and using Flow Channel Inserts (FCIs). In particular, we model their impact on the plant due to changes in the thermohydraulics of the chosen blanket design.

2. Materials and Methods

PROCESS is a comprehensive systems code used to calculate a set of self-consistent parameters for a fusion power plant while ensuring that its operating limits are not violated. It consists of a set of simple physics and engineering algorithms, controlled by user with selected inputs and constraints. In this paper we chose values suitable for an EU-DEMO type reactor based on EUROfusion research and development [see e.g., 6, for MMS design] [see e.g., 5, for SMS design]. For example, we impose the constraint of producing a net electric power of 500 MW and a 2 hour pulse length [the majority of our chosen values are based on the 2018 DEMO baseline, see 7]. PROCESS can also optimise the parameters to maximise or minimise a chosen figure of merit. For the results presented here, we chose to minimise major radius. More detailed information regarding PROCESS, and how the blanket models are used within the code, can be found in Kovari *et al.* [2] and Kovari *et al.* [8].

The EU DEMO DCLL breeding blanket concepts use liquid Lead-Lithium (PbLi) as tritium breeding material, tritium carrier, neutron multiplying material and blanket coolant [e.g., 4]. Helium is used as the coolant for the first wall (FW) and blanket structure while the PbLi cools itself and the FCIs. The PbLi flows though the strong magnetic field of the fusion reactor and therefore experiences Magnetohydrodynamic (MHD) effects. Hence, DCLL designs can include Ceramic FCIs to provide electrical insulation in PbLi channels and minimise the these MHD effects. FCIs are also required to provide thermal insulation for BB designs with high temperatures (i.e., above the allowable temperature limit for EUROFER steel structure).

The DCLL model implemented in PROCESS calculates component volumes, masses and required mechanical pumping power for coolants. Key input information consists of (but is not limited to):

- Selected radial build: radial fractions for the subsections of the FW/BB and material fractions expected for each subsection.
- Number of poloidal and toroidal blanket modules.
- Required pressure and inlet/outlet temperatures for the FW and BB coolants.
- FCI selection: no FCI (in which case Eurofer is assumed), FCI with perfect conductance, or FCI with specified conductance.

This DCLL model also currently requires the user to choose the expected values for the nuclear heating in the FW and BB (input as fractional values for components and selected materials). However, a model, based on ongoing neutronics simulation work, will be implemented in the near future that will account for the effects on the BB heat deposition and tritium breeding ratio (TBR). Energy multiplication in the blankets is assumed to be 1.12 for a DCLL-type design and 1.23 for HCPB for all results reported in this study.

Implementation of a DCLL model in the PROCESS systems code necessitated the refactor and expansion of the current blanket thermohydraulics to include estimates of MHD pressure drops experienced by liquid metal breeder/coolant flow. Pressure drops can be calculated using using either Equation 1 or 2, shown in Table 1, depending on the users chosen inputs. Eq. 1 assumes the the use of perfectly insulating FCIs. Eq. 2 uses a chosen value for the channel wall conductivity, with or without FCIs. Both calculations are only for the long, poloidal channels in the DCLL Breeding Zone (BZ) and assume rectangular-shaped channels. We also assume the use of a Brayton cycle when calculating the thermal-to-electric power conversion efficiency using the PbLi outlet temperature. (??)

	Relation		Source
Perfectly Insulating	$\Delta p = vBl\sqrt{(\frac{\sigma_{liq}\mu_{liq}}{a})}$	(1)	Malang and Mattas [9]
Specified Electrical Conductance	$\Delta p = \frac{C}{1+\frac{a}{3b}+C} \quad \sigma_{liq} v B^2 l$ $C = \frac{r_i}{r_w}$ $r_i = \frac{b}{\sigma_{liquid} a}$ $r_w = \frac{b}{\sigma_{wall} x_{wall}}$	(2)	Miyazaki *et al.* [10]

Table 1. MHD pressure drop (Δp) used in PROCESS. Where v is liquid metal flow velocity, B is magnetic field strength, l is poloidal channel length, a is channel half width in the toroidal direction, b is channel half width in the radial direction, σ_{liq} is liquid metal conductivity, μ_{liq} is liquid metal viscosity, σ_{wall} is channel wall conductivity, and x_{wall} is channel wall thickness.

The pressure relations in Table 1 are both dependant on the magnetic field strength (B), flow channel length (l) and liquid metal flow velocity (v). B is taken to be the toroidal value at the centre of the breeding blanket module and l is calculated using available blanket module volume. Calculation of v depends on user input, either using the required mass flow in the coolant to remove a given heat deposition or the number of required circulations per day. We use the former for the PROCESS DCLL runs reported in this paper. PbLi material properties (density, specific heat, electrical conductivity, dynamic viscosity) are calculated using the temperature relations provided in Martelli *et al.* [11] using the mid-value of the inlet and outlet temperatures.

3. Results

In this section, we present the results of individual PROCESS optimisation runs with different selected input parameters and the results of PROCESS scans, for which a selected input parameter is varied over a chosen range. The key output parameters presented in this paper for the purpose of design choice comparison are: major radius (R), toroidal magnetic field strength at major radius (B_T), and fusion power required to generate 500 MW net electric power (P_{fus}). Table 2 summarises the results for a selection of individual optimisations. Figure 1 shows the modelled power flow for a power plant with an HCPB blanket based on EU DEMO design, used as a reference for comparisons to the DCLL blanket designs modelled in this investigation.

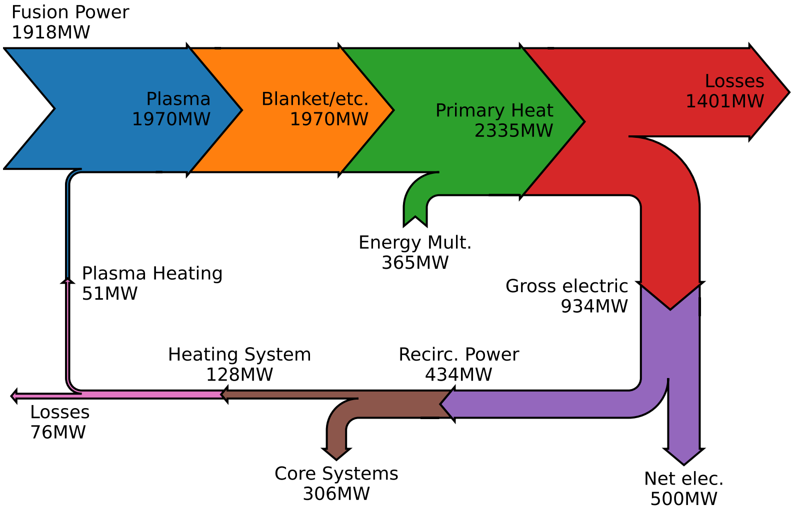

Figure 1. Sankey diagram showing the balance of plant for an EU DEMO fusion power plant with a HCPB breeder blanket, modelled using .

Table 2. PROCESS runs: breeder blanket selected input and output parameters.

BB Type	FCIs[1]	MMS or SMS	Inlet (K)[2]	Outlet (K)[2]	Pressure (Pa)[2]	Power Fraction[3]	FW Pitch (m)[4]	Fusion Power (MW)[5]	R (m)[6]	B_T (T)[7]
HCPB	-	-	-	-	-	-	-	1920	9.04	5.23
DCLL	N	MMS	570	770	-	0.66	0.02	Not	Feasible	
DCLL	P	MMS	570	770	-	0.66	0.02	1862	8.95	5.21
DCLL	P	SMS	570	770	-	0.66	0.02	Not	Feasible	
DCLL	P	MMS	700	800	-	0.66	0.02	1770	8.81	5.17
DCLL	P	SMS	700	800	-	0.66	0.02	Not	Feasible	
DCLL	P	MMS	700	950	-	0.66	0.02	1670	8.66	5.13
DCLL	P	SMS	700	950	-	0.66	0.02	1760	8.80	5.17

[1] Values given for FCIs are the selected conductivity ($AV^{-1}m^{-1}$), if no FCIs (N) are used then conductivity is assumed to be that of EUROFER ($8.33 \times 10^5 AV^{-1}m^{-1}$), if the FCIs are assumed to be perfectly insulating (P) a different pressure drop realtion is used (see Table 1.)

[2] Inlet and outlet temperatures, and pressure are inputs for the PbLi flow.

[3] BB fraction of the combined thermal power absorption of the FW and BB.

[4] Spacing of the FW coolant channels.

[5] Output: Fusion power require for 500 MW net electric power.

[6] Output: Major radius.

[7] Output: Toroidal magnetic field strength at major radius.

It is important to note that using a DCLL model with no FCIs produced unfeasible results for the values tested in this study. Either the MHD pressure drops where much too large for the modelled system; or the pumping power requirement was sufficiently high that PROCESS was unable to find solutions with the constraint of a 500 MW net electric output. All the plotted DCLL results presented within are for blankets with FCIs.

PROCESS output parameters produced from scans over different PbLi outlet temperatures are shown in Figure 2. Higher PbLi outlet temperatures result in a modelled power plant with a lower P_{fus} and smaller R. The SMS version of the DCLL blanket only produced successful runs (i.e., self-consistent and within selected constraints) for higher PbLi temperatures. Successful runs for the DCLL model also require that the difference between inlet and outlet temperatures is sufficiently large: e.g., for the lower temperature

MMS plotted results this difference must be $\gtrsim 70K$ and for the SMS this difference must be $\gtrsim 200K$.

Higher PbLi outlet temperatures result in a more efficient conversion from thermal to electrical energy thereby requiring smaller values of P_{fus} to reach a given net power target. A larger difference between the inlet and outlet temperature results in a smaller mass flow required to remove a given proportion of thermal power from the DCLL PbLi breeder/coolant. This means that the required flow velocity of the PbLi is lower and hence, so are the pressure drops experienced by the flow, resulting in reduced required mechanical pumping power. For the PROCESS runs reported in this study, we chose to minimise R. Therefore, a reduction in the required fusion power to achieve a given net electric output results in a smaller machine build. This has the effect of requiring shorter poloidal PbLi channels and a smaller required B_T. Both of which contribute to the redution of the MHD pressure drops experienced by the PbLi flow, which in turn means that the plant requires less mechanical pumping power. Power plants modelled with DCLL blankets generally result in lower values of P_{fus} than a power plant using a HCPB blanket, the smallest and most efficient power plants modelled were high temperature MMS DCLL blankets.

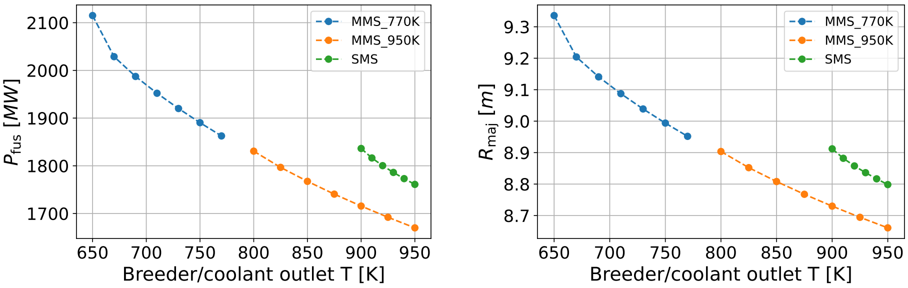

Figure 2. PROCESS output parameters for scans of PbLi outlet temperature. The left-hand and right-hand plots show required fusion power (P_{fus}) and major radius (R) respectively for an MMS DCLL blanket with PbLi temperatures of 570 K (blue) and 700 K (orange), and a SMS DCLL blanket with inlet temperature 770 K (green). The runs for outlet temperatures below 900 K (650 K) returned unfeasible results for the SMS (MMS).

3.1. DCLL - PbLi channel wall elecrtical conductivity

B_T and P_{fus} for scans of PbLi FCI electrical conductivity are shown in Figure 3. Varying the conductivity for PbLi FCI material in an MMS DCLL blanket makes very little difference to the output parameters, provided FCI conductivity is sufficiently low. Above $\sim 1000AV^{-1}m^{-1}$, PROCESS is unable to produce a feasible solution for the MMS DCLL blanket due to high MHD pressure drops in the PbLi channels. This boundary between acceptable and unacceptable conductivity can be adjusted by altering the selected inputs and constraints. Hence, it can be said that for a given set of blanket specifications/plant requirements there will be a limit to the FCI conductivity that produces a feasible power plant design. The SMS version of the DCLL blanket has a lower limit of $\sim 600AV^{-1}m^{-1}$ for the same set of constraints and displays a stronger relationship with conductivity for the acceptable range. The conductivity of a FCI depends on the material selected and the method used to produce the FCI material. For example, Silicon Carbonate, one of the candidate FCI materials, has been shown to have a conductivity of 22 to $660AV^{-1}m^{-1}$ depending on the fabrication techniques [see references within 12]. Hence, desired performance of proposed power plant impacts the manufacturing process most appropriate for FCIs.

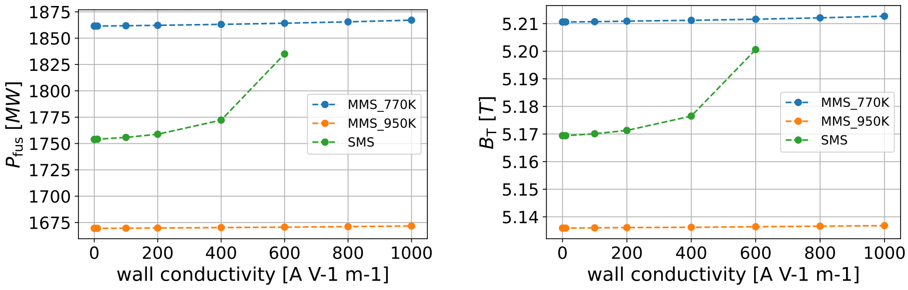

Figure 3. Toroidal magnetic field strength (B_T) and fusion power (P_{fus}) against PbLi channel wall electrical conductivity. The blue, orange and green lines correspond to an MMS DCLL blanket with PbLi inlet-outlet of 570-770 K, MMS DCLL blanket with PbLi inlet-outlet of 700-950 K, and an SMS DCLL blanket with an PbLi inlet-outlet of 700-950 K. Electrical conductivity values above $600AV^{-1}m^{-1}$ gave non-feasible results for the SMS blanket.

3.2. *An example of the effect of BB design on the FW design*

Figure 4 shows P_{fus} against FW cooling channel pitch for runs with DCLL and HCPB blankets. It can be seen that, for all blanket types, increasing the pitch results in an increase in P_{fus}. This is particularly pronounced for the HCPB design, which displays a steep increase in P_{fus}, additionally, PROCESS cannot produce feasible results for the HCPB runs above a pitch of 0.04m. The MMS DCLL blanket requires a lower P_{fus} than the SMS for a given pitch value. Power plants with MMS (SMS) DCLL blankets that have a pitch larger than 0.07 m (0.05 m) do not out perform the EU DEMO baseline for a HCPB which is assumed to have a pitch of 0.02 m. The current EU DEMO DCLL designs have a FW pitch that varies between 0.05 and 0.08 m. The breeding blanket type selection therefore significantly impacts the design of the FW coolant channels and the associated subsystems.

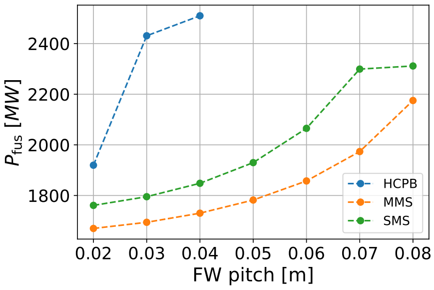

Figure 4. Required fusion power (P_{fus}) for scans of FW channel pitch. The blue, orange, and green lines are for a HCPB, an MMS DCLL (PbLi inlet-outlet of 700-950 K) and an SMS DCLL (PbLi inlet-outlet of 700-950 K) blankets respectfully. FW pitch values above 0.04 gave non-feasible results for the HCPB blanket.

4. Discussion

Systems codes allow the complex interactions between fusion power plant subsystems to be modelled and the relative merits of different design choices to be compared in a holistic manner. This is an important step for the review of each iteration of a fusion power plant design and a highly valuable utility for the selection and design of individual plant subsystems [e.g., 13]. In this investigation, we examined the first results of implementing a DCLL model in the PROCESS systems code and compared our results to the existing PROCESS baseline for an EU DEMO-type power plant with a HCPB blanket.

A DCLL blanket design has many possible advantages, these include: using one material for the three tasks of tritium breeding, neutron multiplication and absorption of nuclear power; and the potential to allow higher coolant outlet temperatures, suitable for a more efficient Brayton cycle thermal-to-electric power conversion system [e.g. 3,14]. The SMS version of the DCLL blanket design also has the additional potential advantages of design simplicity and reliability [e.g., 5]. However, a major disadvantage of a DCLL design, or any fusion breeding blanket design which incorporates liquid metal flows, is the need to account for MHD pressure drops in the breeder/coolant pipes. Materials are required that are capable of electrically and thermally insulating the liquid metal, while withstanding corrosion and a high temperature, high radiation environment [15]. This is particularly true for SMS DCLL designs with very long poloidal flow channels that are subject to greater pressure drops and larger increases in PbLi temperature.

In this study, we implemented a DCLL blanket model in PROCESS, an established systems code used to investigate fusion power plant designs. Our model estimates the effect of MHD pressure drops on the PbLi breeder/coolant flow and the addition of FCIs with varying electrical conductivity. Our results confirm that a power plant using a DCLL blanket could thermohydraulically outperform a plant using a HCPB blanket, despite the lower expected energy multiplication of DCLL blankets compared to HCPB. However, these results are design dependant and rely heavily on the ability to develop and manufacture FCIs that are sufficiently electrically and thermally insulating. The effect of design choices is also more pronounced for the SMS type DCLL blanket, highlighting the importance of using systems modelling to evaluate power plant design choices for advanced component concepts.

Our results indicate that there are potentially significant benefits to using a DCLL blanket in a fusion power plant, that may result in smaller machines which require less fusion power to achieve a net electric goal. A smaller, less powerful machine has advantages such as less massive components, with associated cost and maintenance benefits, and lower neutron fluences, hence, longer operating lifetime for components. Planned future work includes further investigation into the effect of using a DCLL blanket on power plant design (e.g., availability) and a comparison between the DCLL and the Helium Cooled Lead-Lithium (HCLL) blanket designs for EU DEMO. The DCLL model will also be expanded to include estimates of blanket TBR and neutron power deposited in the blanket that makes use of a neutronics simulation database.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BB	Breeding Blanket
BZ	Breeder Zone
DCLL	Dual-Coolant Lead-Lithium
FCI	Flow Channel Inserts
FW	First Wall
HCPB	Helium Cooled Pebble Bed
HCLL	Helium Cooled Lead-Lithium
MHD	Magnetohydrodynamic
MMS	Multi-Module Segment
PbLi	Lead-Lithium
SMS	Single Module Segment
TBR	Tritium Breeding Ratio

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