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Abstract

Development of a DEMO Helium Cooled Pebble Bed (HCPB) breeder unit featured in flat plates with meandering channels

During the design review in 2003, the modular HCPB blanket concept with a cellular breeding region was proposed and accepted as an EU reference. The concept offers the flexibility of designing 200 x 200 x 500 mm^3 breeder units virtually independently of the blanket box. Recently it has been found that ceramic breeder containers featured in the current breeder unit design could see high levels of secondary stress and need to be amended. Scoping calculations have shown, however, that an alternative design based on flat plates with meandering cooling channels meets neutronics requirements, despite a decrease in the content of ceramic breeder and beryllium. This design would also help increase the common features and manufacturing steps of HCPB and HCLL concepts.
In this report, a new HCPB breeder unit based on the design featured in flat plates is developed. Supporting analyses in neutron physics, thermal-hydraulics and structure mechanics are carried out to check (i) the capability of reaching tritium breeding sufficiency, (ii) the adherence to maximum temperatures in structural and functional materials and (iii) the abidance by the stress criterion imposed by the structural material. Manufacturing sequences of the breeder unit are defined. Finally possible improvements of the new designed breeder unit are proposed.

Kurzfassung

Entwicklung der DEMO Helium Cooled Pebble Bed (HCPB) Brütereinheit in Gestaltung von ebenen Platten mit Meander-Kanälen

Während der Entwicklungsoptimierung im Jahre 2003 wurde das modulare HCPB Gesamtkonzept mit einer zellenartigen Brüterzone vorgeschlagen und als EU Referenz anerkannt. Das Konzept beschreibt die Konstruktion von anpassungsfähigen 200 x 200 x 500 mm^3 Brüter-Einheiten, die nahezu unabhängig vom Hüllcontainer sind. Neuste Erkenntnisse ergaben, dass keramische Brütereinheiten im bestehenden Design sehr hohe Sekundärspannungen erfahren und dahingehend berichtigt werden müssen. Abgrenzende Kalkulationen hieraus zeigten, dass ein alternatives Design, basierend auf ebenen Platten mit Kühlkanälen in Meander-Form, die neutronischen Belange trotz einer Abnahme der Menge an keramischem Brütermaterial und Beryllium erfüllen. Diese Änderung im Design verbessert, neben den generellen Eigenschaften, auch die Herstellbarkeit der HCPB und HCLL Konzepte. In diesem Bericht wird die Entwicklung des neuen Konzeptes der HCPB Brütereinheit, basierend auf der Eigenschaft von ebenen Kühlplatten, beschrieben. Unterstützend werden hierzu Analysen in Neutronenphysik, sowie thermohydraulischer und strukturmechanischer Sicht durchgeführt um (i) das Potenzial der zu erreichenden Tritium Brüterrate, (ii) die Abhängigkeit zu den Maximaltemperaturen in den Struktur- und Funktionsmaterialien sowie (iii) die Einhaltung der Spannungskriterien, die durch das Strukturmaterial hervorgerufen werden, zu ermitteln. Ebenso werden die hierfür erforderlichen Herstellsequenzen der Brütereinheit beschrieben. Abschließend sind weitere mögliche Verbesserungen der neu gestalteten Brüter-Einheit vorgestellt.

CONTENTS

1 Introduction

The Helium Cooled Pebble Bed (HCPB) blanket has been selected as one of two European reference concepts for a DEMO nuclear fusion reactor for nearly a decade [1], because HCPB blanket has a reasonable high thermal efficiency, good safety features and compatibility between coolant, structural and functional materials. European Power Plant Conceptual Study (PPCS) [10] indicates that the HCPB blanket by using reduced-activation ferritic martensitic steel EUROFER as structure material is a feasible scheme with only limited extrapolation of the current engineering technology. In the blanket design review in 2003, a modular HCPB blanket concept with a cellular breeding region was initiated and accepted as an EU reference [3]. A big advantage of the modular design is that it is flexible to design a breeder unit (BU) almost independently on the blanket box.

In the last design of BU, a scheme about two double-bed breeder containers in "∃" shape was adopted [4]. The breeder containers are cooled by a group of parallel inner cooling channels. The investigations on th0is proposal have been focused on the two critical aspects of the proposed design: the necessary fabrication technologies and the thermo-mechanical performances. However no suitable solution has been found for both aspects. The design should cope with the difficult T-welding of the cooling plates at the plasma side. The computational simulation in thermal state shows that an unacceptably high stress appears in the structure. In order to remove it further complications in the design should be introduced. Therefore a new design based on flat plates with meandering cooling channels is proposed in this report, and numerical analyses about the new design have been done to support it.

Section 2 presents the design requirements of BU in some important views as neutron physics, material science, thermal-hydraulics, structure mechanics and so on. The layout of BU is described in section 3. Section 4 describes the results of neutronics analysis. Section 5 and 6 discuss the supporting analyses by using the commercial code ANSYS. The fabrication procedure is defined in section 7. Finally the work about this project is summarized and future work is proposed.

2 BU design requirements

The BU design is determined by many aspects, in general, like blanket functions, material interactions or compatibility, thermal limits and structural stress limits, reliability and availability, economics and so forth [5]. Five important requirements imposed by different aspects are listed below.

- In view of neutronics, the BU should be able to breed tritium that can be contributed to the plant fuel cycle, and the design should assure a good release of tritium from the ceramic breeders, i.e. a prescribed value of tritium breeding ratio (TBR) must be reached. In addition the BU must supply good neutron shielding for the parts behind the blanket.

- The design should guarantee a maximal average temperature of the ceramic in order to facilitate the tritium release (reducing the tritium residence time) and to minimize the inventory of tritium in the ceramic beds. Of cause a purge gas system in low pressure must be designed to collect tritium and remove it from the breeder and multiplier pebble beds.

- In view of material science, the neutron multiplier, the tritium breeder, the coolant and the structure plate have to be compatible to each other, even under operating and off-design scenarios.

- In view of thermal-hydraulics, the BU is the basic unit of heat production and removal by a cooling circuit; therefore, the coolant system must be effective enough to cool the pebble beds and the steel plates in the BU, in order to keep the peak temperatures of different materials below the corresponding permissible temperature limits; on the other hand, the less the pressure drop of the coolant loop is, the better it is to keep the overall pumping power at a value compatible with a good efficiency of the power generation systems.

- In view of structure mechanics, the maximal stress distributed in the supporting steel structure of the BU has to be less than the permissible value of the material especially under thermal loads.

In addition, the industrial conditions qualified to manufacture the BU have to be consistent to the existing fabrication technologies. The feasibility has to be investigated if any technical extrapolation is needed.

3 BU design descriptions

A standard modular blanket box consists of 9 × 9 BUs and a stiffening grid, enveloped by a front wall or first wall (FW), two side walls, two caps and a back plate with manifolds. The BUs with poloidal × toroidal × radial dimensions of 205×205×480 mm^3 can be inserted into the blanket box, like drawers into a chest. The environment of the BU is shown in Figure 3.1.

Based on the HCPB concept, the BU is principally made from pebble beds, tritium breeder and neutron multiplier, cooled by EUROFER steel plates that separate beds. The steel plates themselves are cooled by the internal meandering helium flow channels. In this design, lithium ceramic material, Li_4SiO_4 or Li_2TiO_3, is used as tritium breeder, and beryllium as the neutron multiplier. Both of them are in form of pebble beds. In the new design, four ceramic beds are enclosed in four separate canisters, each of which is delimited by two cooling plates and a steel wrapper, as shown in Figure 3.3. Beryllium beds are filled in the interval spaces between the canisters. At the radial rear end, the BU is closed by a back plate with imbedded piping system of helium including tritium purge system. The helium loop in the BU is designed at a pressure of 8 MPa and a temperature of 400 – 500 °C. The lay-out of the BU is shown in Figure 3.2.

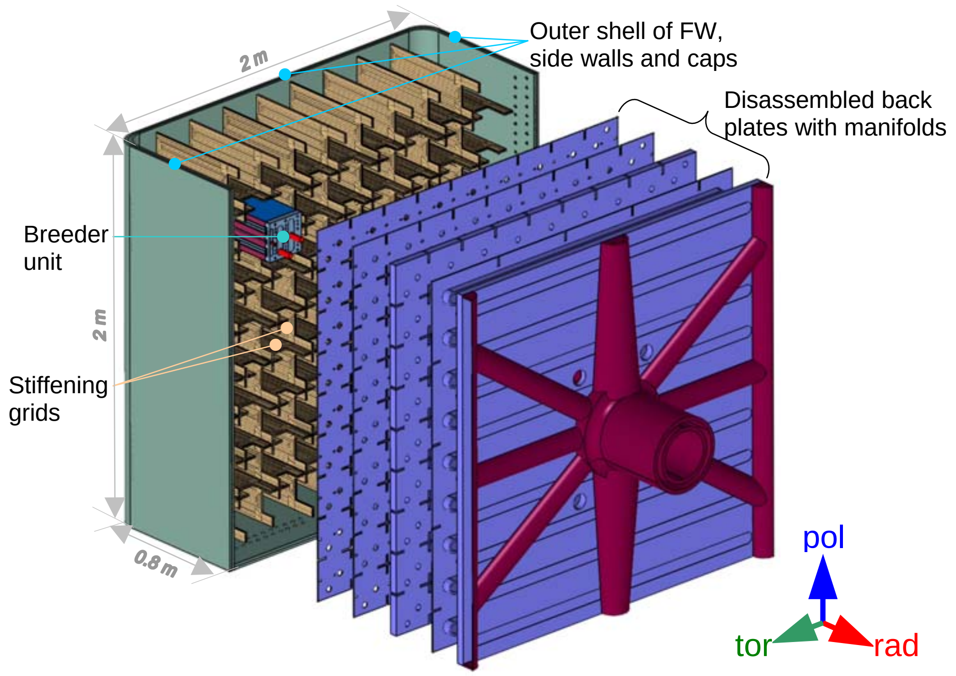


Figure 3.1 Physical boundary of BU in blanket box

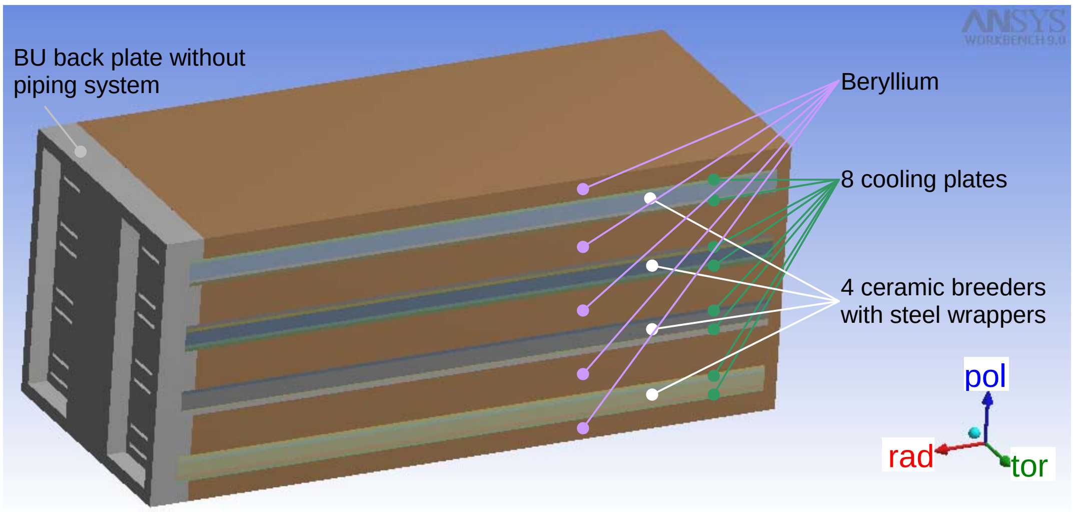


Figure 3.2 BU design model

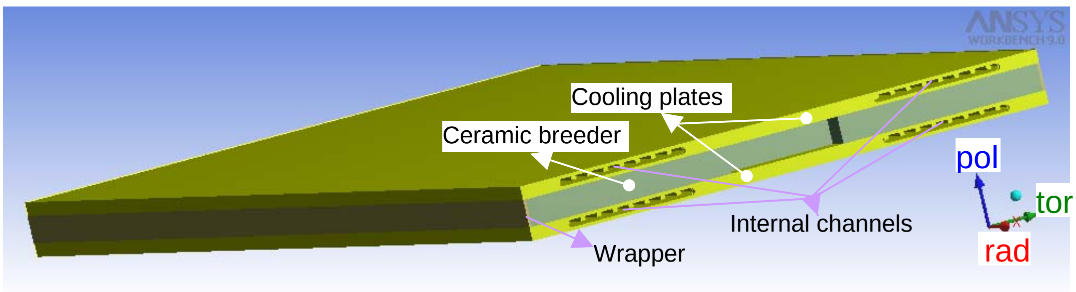


Figure 3.3 Example of breeder canister

According to the materials adopted in the design, the following design criteria have been defined.

- The material composition must be in a good range in order to assure the tritium self-sufficiency of the fusion reactor.

- The design temperature limit of ceramic breeder Li_4SiO_4 is 920 °C, which is about 100 °C lower than the melting point.

- The design temperature limit of beryllium is assumed here as 650 °C [6], which is determined by the mechanical behaviors of beryllium pebble bed under certain temperature and pressure. This value doesn't represent a physical limit; it needs to be explored in further research if higher temperature limits can be assumed.

- The design temperature limit imposed by the EUROFER steel is about 550 °C, which is determined by the creep strength of EUROFER [7].

- The thermal stress limit, 3Sm, of EUROFER steel is about 351 MPa at 550 °C [7].

In order to satisfy both temperature limits and the requirement of TBR, i.e. tritium breeding sufficiency, the selection of the breeder pebble bed heights is an optimization problem. That is, an optimal dimension allocation between breeder pebble bed height and beryllium pebble bed height must be obtained by some times of trial calculations. Table 3.1 shows the critical dimensions and some characteristic parameters about the pebble beds in a reference design.

Table 3.1 Geometrical settings and descriptions of BU in a reference design

	Poloidal height	Descriptions
Ceramic pebble bed	4 × 10 mm	– Li_4SiO_4 in 40 at% ^6Li enrichment – Poly-disperse pebble – Particle size 0.25 – 0.63 mm – Packing fraction 64.5%; the remaining fraction is helium at about 0.12 MPa – Breeder wrapper in steel with 1 mm thick
Beryllium pebble bed	3 × 30 mm, 2 × 17.5 mm	– Beryllium – Mono-disperse pebble – Particle size 1 mm [6] – Packing fraction 63.5% [6]; the remaining fraction is helium at about 0.12 MPa
Steel cooling plate	8 × 5 mm	– EUROFER – Flat plate with inner meandering cooling channels – Channel dimension 2.6 × 4.5 mm^2
Whole BU	205 mm	– Toroidal width 205 mm – Radial length 480 mm

The material composition is a critical index for neutronics performance of the breeding blanket of a fusion facility. In terms of BU, the fractions of different materials have to be balanced among neutron multiplier, tritium breeder and shielding or structure materials. The specific layout of the functional materials in the BU is certainly important but less explicit. The material composition of the reference design of BU is listed in Table 3.2.

Table 3.2 Material compositions in BU

	Volume, $\times 10^{-5}$ m^3	Volumetric fraction, %	Mass, kg	Mass fraction, %
Li_4SiO_4 [a]	375	19.5	5.736	14.4
Beryllium [a]	1208	62.7	18.120	45.6
EUROFER [b]	205	10.6	15.888	40.0
Helium [c]	139	7.2	0.0075	0.018
Whole BU	1927	100.0	39.752	100.0

[a] Packing effect must be and is already considered here while calculating mass inventory of pebble beds.
[b] Parts made in EUROFER include cooling plates, breeder wrappers and a back plate.
[c] Reference pressure 8 MPa and reference temperature 450 °C.

4 Neutronics analyses

Neutronics calculations for the modular blanket with stiffening grid and horizontally inserted BUs have been done [2] by using a three-dimensional Monte Carlo simulation MCNP computer code [8], based on a suitable 9° torus sector model and a nuclear cross-section data library from Fusion Evaluated Nuclear Data Library FENDL-2 [9]. Reactor parameters being used in the analysis are from the model B, featured in HCPB blanket, of European PPCS, which is a big model with major and minor radii of 8.6 m and 2.8 m, respectively, total fusion power of 3300 MW, average neutron wall load of 2.0 MW, average surface heat load of 0.4 MW and with a 2 mm thick tungsten layer for protecting the first wall [10]. The main results of neutronics analyses about the reference design of BU are summarized as follows.

- TBR. In the reference case, 4 single ceramic breeder pebble beds with 10 mm poloidal height and 460 mm radial length, made in Li_4SiO_4 with 40 at% ^6Li enrichment, can supply a neutron multiplication factor of 1.65, and a TBR of 1.119. This value is principally high enough to cover the loss of blanket coverage primarily owing to ports penetrating the blanket, and to compensate the uncertainties of the nuclear cross-section data.

- Shielding. Neutron shielding, specially shielding against fast neutrons, is realized by the radially thick beryllium pebble bed due to the fact that beryllium is a very effective neutron moderator and can attenuate the fast neutron flux density very efficiently. On the other hand, the back plate at the radial rear end of the BU is designed as a high temperature shielding in addition to supplying the basic support to the whole BU and to closing the pebble beds.

– Heat power distribution. It is an important boundary condition for the following thermal analyses. The heat power distribution in different material layers, obtained by neutronics analyses, is showed in Table 4.1. As can be seen from the table, the power density drops down approximately in an exponential way along with the increase of the distance from the FW.

Table 4.1 Heat power distributions in beryllium, lithium ceramic and EUROFER steel, as functions of radial distance from the FW

Radial distance from FW, $\times 10^{-3}$ m	Heat power density, $\times 10^6$ W/m^3		
	Beryllium	Lithium ceramic	EUROFER steel
2			17.70361
7			17.28491
27			16.21081
31	8.05993		
42	7.17110		15.33061
47	7.17110	28.79911	14.08261
77	5.97611	25.67761	12.33871
107	4.98896	23.05841	10.58541
137	4.12316	20.94081	8.87861
167	3.41272	18.49051	7.53569
197	2.79817	16.54371	6.43618
227	2.30114	14.33161	5.36706
257	1.88642	12.73261	4.51292
287	1.54578	10.88561	3.78544
317	1.28374	9.45581	3.20394
347	1.62144	8.20200	2.69031
377	1.31671	7.06347	2.24843
407	1.08477	6.17779	1.92697
437	0.910289	5.29404	1.62741
467	0.754197	4.74914	1.38679
502			

5 Thermal-hydraulics analyses

5.1 Motives

The primary objectives of thermal-hydraulics analyses are to find out the temperature distributions in the BU under intense heat loads, and to make clear the thermal-hydraulic behaviors of the helium flows in the cooling plates, such as the overall pressure drop. In other word, the design has to be validated in view of thermal-hydraulics. In addition the analyses also initiate new ideas to update the BU design. For an instance, in order to obtain a better layout, i.e. better cooling effect, of the meandering channels in the steel plates, iterations have been done between designs and calculations. It is nearly an optimization process.

It is also the task of thermal-hydraulic analyses to find out the maximal temperature information in the different functional materials of the BU. The rule about temperature limits imposed by the material characters must be observed.

The finite element (FE) analysis is done by using commercial computer codes of ANSYS Workbench and Classic ANSYS 9.0.

5.2 Geometrical models

Considering the symmetries of the BU itself and its boundary conditions, only lower half in poloidal direction of the BU is modeled. The geometrical model is shown in Figure 5.2.1. A mesh with about 700,000 nodes is created for FE analyses, as shown in Figure 5.2.2. Figure 5.2.3 shows an example about the design of meandering helium channels in a cooling plate with half thickness. In the example, totally, 12 channels are designed. 6 outer channels go in a "U" shape, 2 channels meander mainly in toroidal direction, and 4 inner parallel channels meander primarily in radial direction. The following section about the cooling plate design optimization manifests that this layout of meandering channels possesses quite good cooling effect and rather low pressure drop of the helium flow, comparing to other designs.

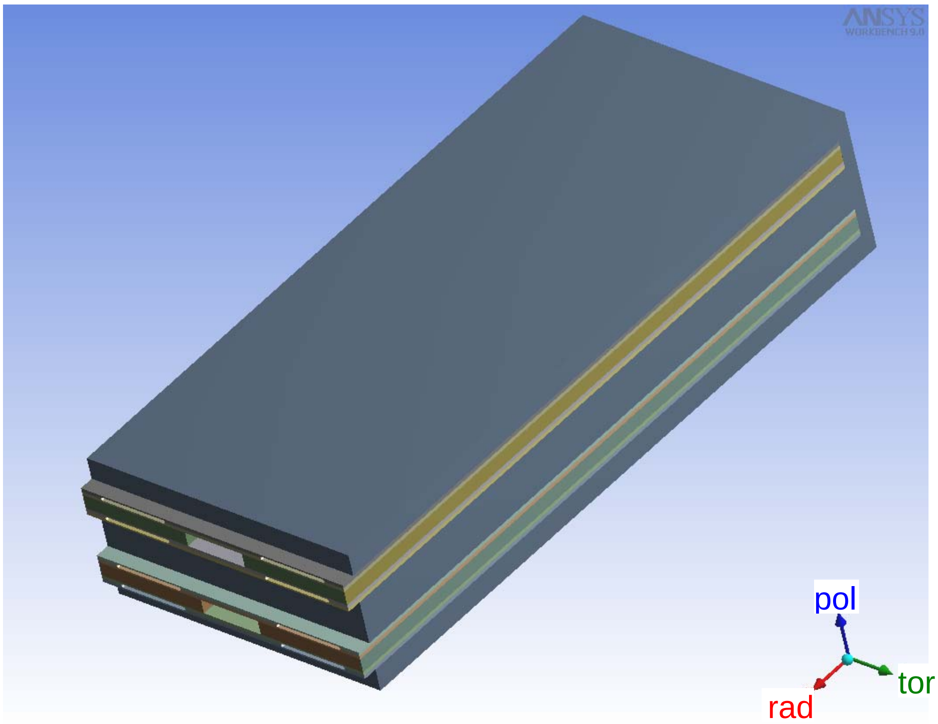


Figure 5.2.1 Geometrical model of lower half of BU

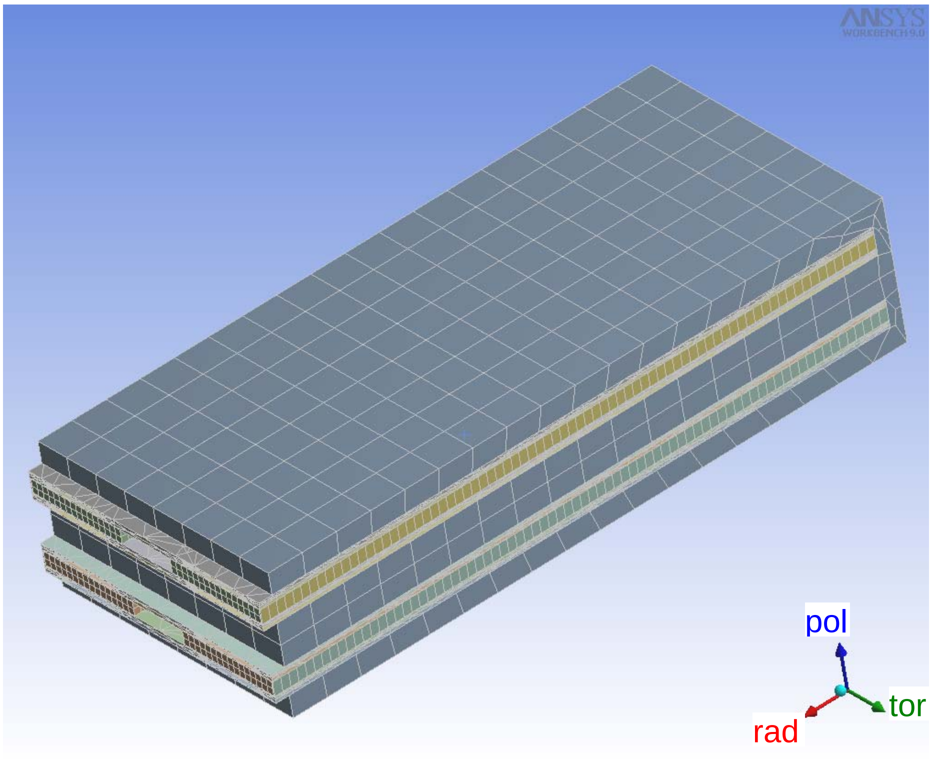


Figure 5.2.2 Geometrical model with mesh

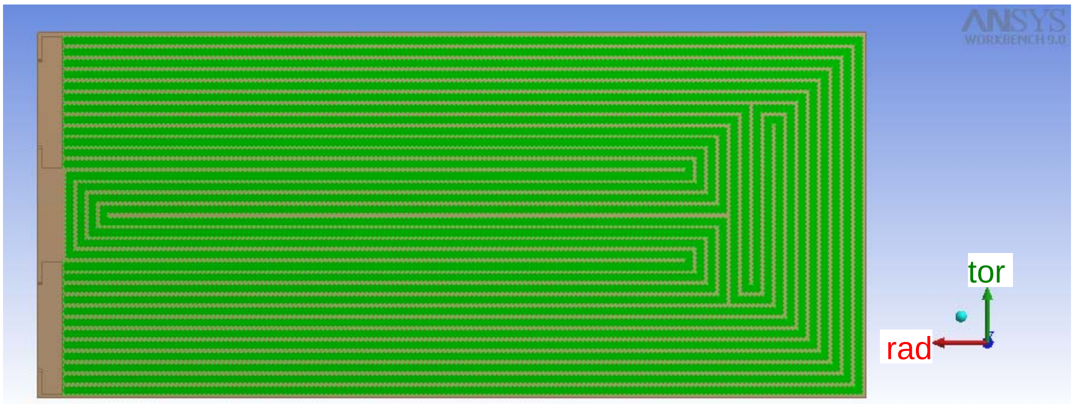


Figure 5.2.3 Meandering channel design in cooling plate

5.3 Material properties

Four materials are involved in the analyses. Most material properties are applied temperature dependent [11]. The material properties or correlations used to calculate them are listed in Table 5.3.

Table 5.3 Material properties at temperature T in K

	Heat capacity, J/kg/K	Conductivity, W/m/K	Density, kg/m^3
Breeder	$940+1.46T+4.011\times10^{6}T^{-2}$	$0.768+4.96\times10^{-4}[T-273.15]$	1529.6
Beryllium	$2353+0.632T+1.07\times10^{-4}T^{2}-6.52\times10^{7}T^{-2}$	10 [a]	1500
EUROFER	600	31	7750
Helium [b]	5200	$3.623\times10^{-3}T^{0.66}$	[c]

[a] Thermal conductivity of beryllium pebble bed is highly dependent on bed compression and thus accessible only to a special thermal-mechanical model. 10 W/m/K is expected to be in the region under operating conditions [12].

[b] Helium viscosity, μ, is given by $\mu=4.646\times10^{-7}T^{0.66}$ in kg/m/s.

[c] Helium density, ρ, is determined by $\rho = \frac{pM}{RT}$, where p stands for pressure, M for molecular weight of helium, R for ideal gas constant, T for temperature.

5.4 Fluid model

5.4.1 FLUID116 element type

Helium is the only fluid in the system, in which the cooling helium flow is primarily confined in small channels or pipes with square cross-section. As FLUID116 element type is in ANSYS simulations a three-dimensional element with the ability to conduct heat and transfer fluid between nodes [13]. It is very suitable to model such kind of flows. Convections between flows and walls can be modeled by using a film coefficient, which is related to the mass flow rate. Therefore, the channel walls should be modeled, in ANSYS, by using SURF152 element type. As the name says, SURF152 is a kind of surface element. The coupling between flow element (FLUID116) and the corresponding wall surface element (SURF152) with a film heat transfer coefficient models the mass flow behaviors taking place in the channels. Figure 5.4.1 shows an example about the helium flow model in 12 channels. Each yellow line stands for the flow in one channel. It is meshed with FLUID116 elements. Correspondingly, the coupled wall surfaces of each “fluid-line” are meshed and specified as SURF152 elements.

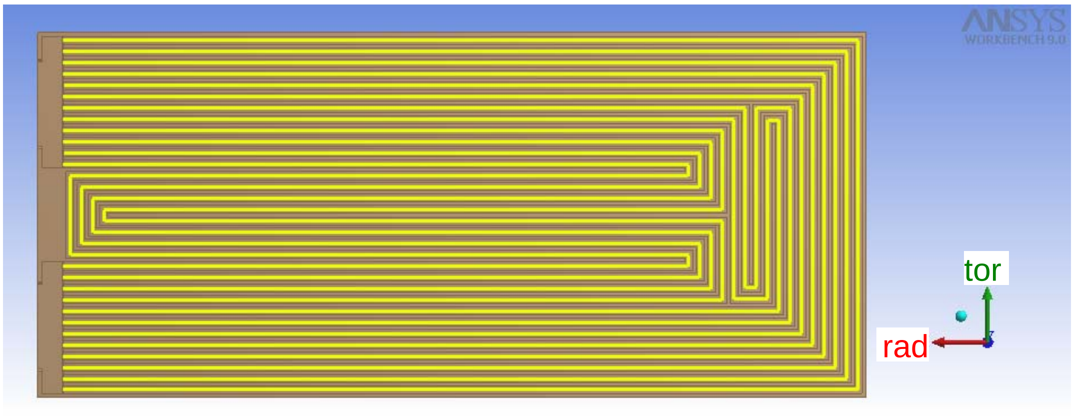


Figure 5.4.1 Fluid model in cooling plate

5.4.2 Mass flow rates

According to a layout calculation for the whole blanket, the overall mass flow rate for one blanket box is about 12.7 kg/s. In each box, there are 9 × 9 BUs, each of which is cooled by 8 cooling plates. Assuming that every cooling plate has the same hydraulic environment, namely that each plate allows the same mass flow rate, then the mass flow rate of one cooling plate is 19.630 g/s, which can be known by a simple arithmetic. Among the meandering channels in the same cooling plate, a problem of mass flow balancing arises, for the reasons that different channels have different hydraulic characters, e.g. various lengths of flow paths and different numbers of bends, and that all the channels share the same overall inlet and overall outlet, i.e. they should have the same pressure drop.

Based on this idea, a pre-calculation by using a self-made C program is done to determine the mass flow distribution among, e.g. 12 meandering channels in the reference case. The key correlation used to determine pressure drop [14] in a straight channel or pipe is given as,

$$\Delta p = \varsigma \frac{l}{D}\frac{\rho V^2}{2}, \quad \frac{1}{\sqrt{\varsigma}} = -2\lg\left[\frac{2.51}{\mathrm{Re}\sqrt{\varsigma}} + \frac{K/D}{3.71}\right]$$

where,

Δp -pressure drop, Pa;	ς -pressure drop coefficient;
l-length of flow path, m;	D-hydraulic diameter of flow channel, m;
V-flow velocity, m/s;	ρ-density, kg/s;
Re-Reynolds number;	K-roughness of wall surface, m.

Pressure drop for a 90° bend is determined by,

$\Delta p_b = \varphi \frac{\rho V^2}{2}$, where, φ is a pressure drop coefficient caused only by geometrical variation.

Figure 5.4.2 gives the mass flow distribution among 12 channels of the example geometrically shown in Figure 5.2.3. In the example, the first 6 channels go in "U" shape with only two 90° bends, then they have higher flow rates than other 6 channels. On the other hand, the flow rate increases slightly from the 1st though 6th due to their shrinking channel lengths in that order. The last four channels have the lowest flow rate because they have the longest flow distance, although they have the same number of six 90° bends as the 7th and 8th channel have. With this mass flow distribution, the pre-calculation gives a pressure drop for every channel of 29,427 Pa, which is relatively low, and where the lower the better.

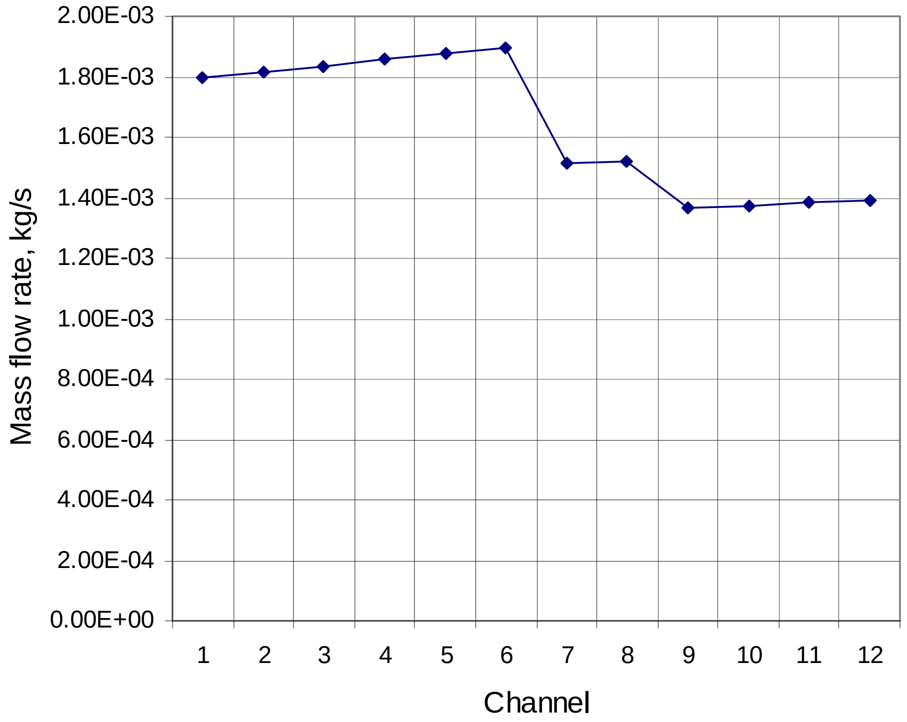


Figure 5.4.2 Mass flow rate distribution among meandering channels

5.4.3 Heat transfer coefficients

The heat transfer coefficients (HTC) between helium flows and walls are influenced by the mass flow rates. Therefore, a mass flow distribution must present differences of HTC among channels. The pre-calculation conducted by the C program also supplies the varying HTCs for different channels. The correlations used to determine the HTC [15] are given here,

$$\alpha = \frac{kNu}{D}, \; Nu = \frac{(\zeta/8)\,\mathrm{Re}\,\mathrm{Pr}}{1+12.7\sqrt{\zeta/8}(\mathrm{Pr}^{2/3}-1)}\left[1+\left(\frac{D}{l}\right)^{2/3}\right], \; \zeta = (1.8\lg\mathrm{Re}-1.5)^{-2}$$

where,

α-HTC, W/m^2/K;	k-thermal conductivity, W/m/K;
Nu-Nusselt number;	D-hydraulic diameter of flow channel, m;
Re-Reynolds number;	Pr-Prandtl number;
ζ-an intermediate parameter;	l-length of flow path, m.

5.5 Boundary conditions

Based on the model defined in section 5.2, the thermal boundary conditions must be specified at the radial front wall abutting upon the FW, the rear walls at the side of the back plate, the walls neighboring to the stiffening grids in both vertical and horizontal directions, and a symmetric boundary at the symmetry plane. The heat transfer boundary at the interfaces between solid plates and pebble beds are specially specified. Finally the boundary conditions at the helium inlet and outlet, and the fluid/solid coupling have to be given.

- Front walls at the side of the FW. A proper HTC of 5000 W/m^2/K between the BU and the FW is specified with an assumed FW temperature of 395 °C [4].

- Rear walls at the side of the back plate. An adiabatic boundary condition is given conservatively.

- Walls adjacent to the stiffening grids. The most contacts between the BU and the stiffening grids are beryllium/steel interface. Therefore a convection boundary with an HTC of 4000 W/m^2/K and an ambient temperature of 450 °C is given for the boundaries.

- Interfaces between pebble beds and steel plates. The heat exchange between piles of particles and a solid wall can be influenced by many factors, such as the particle size, bed compression, swelling extent of pebbles under irradiation. Therefore the exact HTC at this kind of boundary is accessible only to an advanced thermal-mechanical model about pebble beds or sophisticated pebble bed experiments under high temperature, high pressure and intense neutron irradiation. The HTC of 4000 W/m^2/K for beryllium/steel contact, and 6000 W/m^2/K for lithium ceramic/steel contact are recommended [4].

- Inlet and outlet of helium flow. A boundary of mass flow rate for helium inlet is applied. The inlet temperature is assumed as 400 °C, and the mass flow rate is obtained by the lay-out calculation in section 5.4.2. Based on the configuration, the average outlet temperature is about 500 °C.

- Fluid/solid coupling. The HTCs between helium flow and steel walls are supplied by the lay-out calculation in section 5.4.2.

Another important boundary is the heat source. The spatially varying volumetric power density is obtained by neutronics analyses in section 4 and is applied as a boundary condition in the thermal analyses.

5.6 Simulation results

In terms of the model defined in section 5.2 as the reference case, a steady state FE simulation has been done by using ANSYS. The simulation results about temperature fields distributed in the BU are exported as pictures.

The overview of the temperature distribution on the half BU model is shown in Figure 5.6.1. The maximal temperature, 615 °C, shown in this picture, must be the peak temperature in beryllium because of the symmetric plane cutting though the middle of the beryllium in poloidal height. According to the picture, it is easily to judge that the end with higher temperature must be the front side, close to the plasma.

A temperature distribution in a poloidal-radial cross section is shown in Figure 5.6.2. The cross section is located intentionally at the point with highest temperature of the model, which must be the peak temperature of lithium ceramic, 902 °C. The similarity about temperature in the two breeder pebble beds can be found in the picture, and both of them present a very strong profile in radial direction, which reflects the exponentially declining feature of the power density distribution.

A temperature field in the steel plate is shown in Figure 5.6.3. As can be seen from it, the high temperature zone mainly belongs to the meandering channels, and is located at the stretches on the side of the outlet. The maximal steel temperature is about 549 °C.

The peak temperatures of beryllium, lithium ceramic and EUROFER steel, observed in the simulation are 615 °C, 902 °C, 549 °C respectively. The three temperatures are all below the corresponding material temperature limits, 650 °C, 920 °C and 550 °C, respectively.

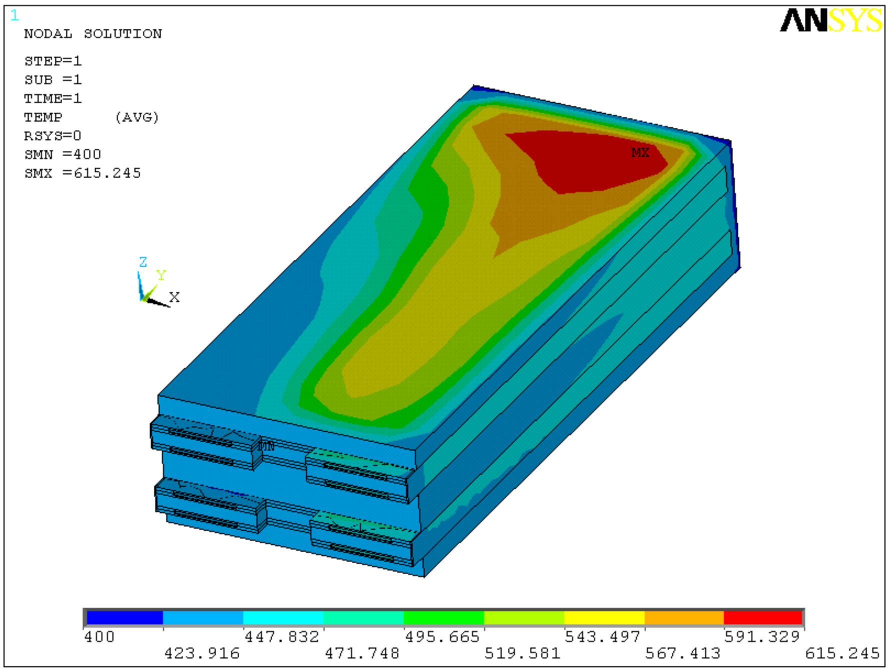


Figure 5.6.1 Temperature overview

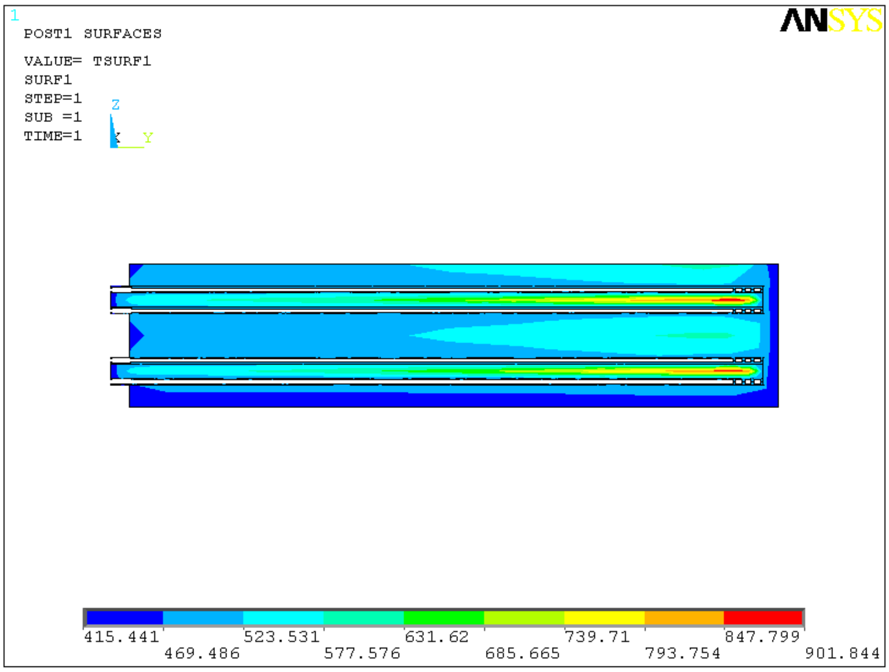


Figure 5.6.2 Temperature distribution in poloidal-radial cross section

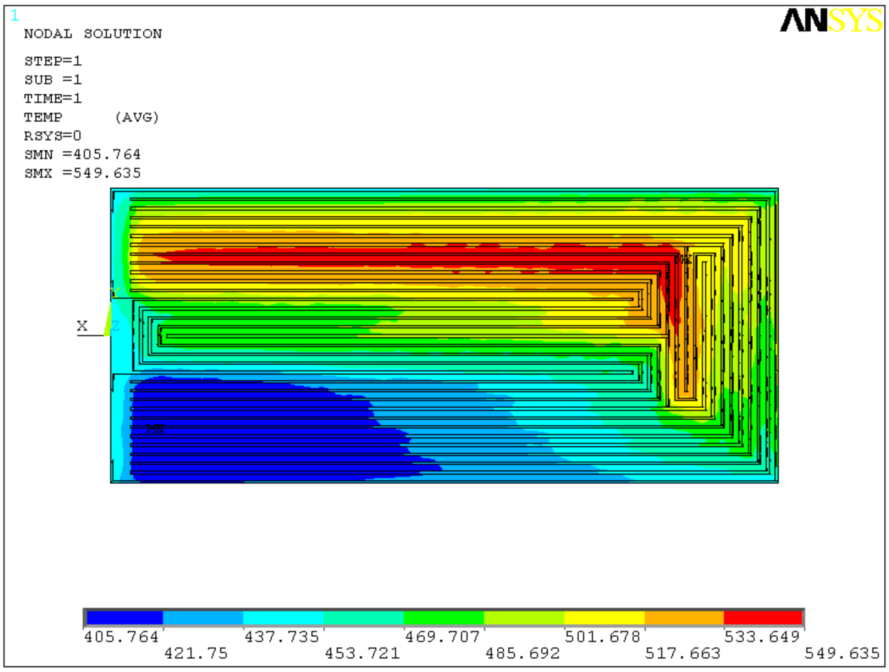


Figure 5.6.3 Temperature distribution in steel plate

5.7 Discussions

5.7.1 Summary of thermal-hydraulics analyses

The primary thermal-hydraulic parameters being used in the numerical model or obtained by the simulations are listed in Table 5.7.1.1, based on the reference case. The heat generations and depositions in one BU are summarized in Table 5.7.1.2.

Table 5.7.1.1 Thermal-hydraulic parameters of BU

Number of channels in one cooling plate	12
Channel dimension	2.6×4.5 mm^2
Helium system pressure	8 MPa
Mass flow rate per channel	1.365×10^{-3} – 1.898×10^{-3} kg/s
Flow velocity	21.9 – 30.5 m/s
Reynolds number	10,730 – 14,926
Inlet temperature	400 °C
Outlet temperature	509 °C (average)
Heat transfer coefficient in channel	2,854 – 3,623 W/m^2/K
Pressure drop	29,427 Pa
Maximal temperature in ceramic breeder	902 °C
Maximal temperature in beryllium	615 °C
Maximal temperature in steel	549 °C

Table 5.7.1.2 Heat generations and depositions of BU

Heat generation in beryllium pebble beds	36.3 kW	(35%)
Heat generation in breeder pebble beds	51.7 kW	(50%)
Heat generation in steel plates	15.7 kW	(15%)
Overall heat power of one BU	104 kW	(100%)
Heat removal from BU to FW	4.67 kW	(4.5%)
Heat removal from BU to stiffening grids	12.5 kW	(12%)
Heat removal by helium loop	86.8 kW	(83.5%)

5.7.2 Layout optimization of meandering channels

The reference design about the meandering arrangement, mentioned in the last sections, is a result of comparison of up to six schemes. Two rules being observed in meandering channel designs are listed below.

- Cooling effect. The channels should be arranged in the way that the heat can be conducted efficiently to cool the pebble beds and the plates in order to satisfy the material temperature limits. In the BU design of 4 single breeder pebble beds with 10 mm poloidal height, the strongest constraint about temperature among the three functional materials is the one of steel. Therefore, the peak steel temperature is an index to adjudge a design.

– Pressure drop. Less pressure drop of helium loop can benefit to save the space within the fusion facility because of a smaller scale of a helium pump. Thus pressure drop has to de considered while designing the cooling plates.

The six designs are shown together in Figure 5.7.2. Their design features are summarized in the following Table 5.7.2. And the results of thermal-hydraulic analyses by applying a 1/8 BU model are listed in the right two columns in Table 5.7.2. This model includes a half breeder bed, a half beryllium bed and a cooling plate in between. The detailed description about the simplified model is given in section 6.2.

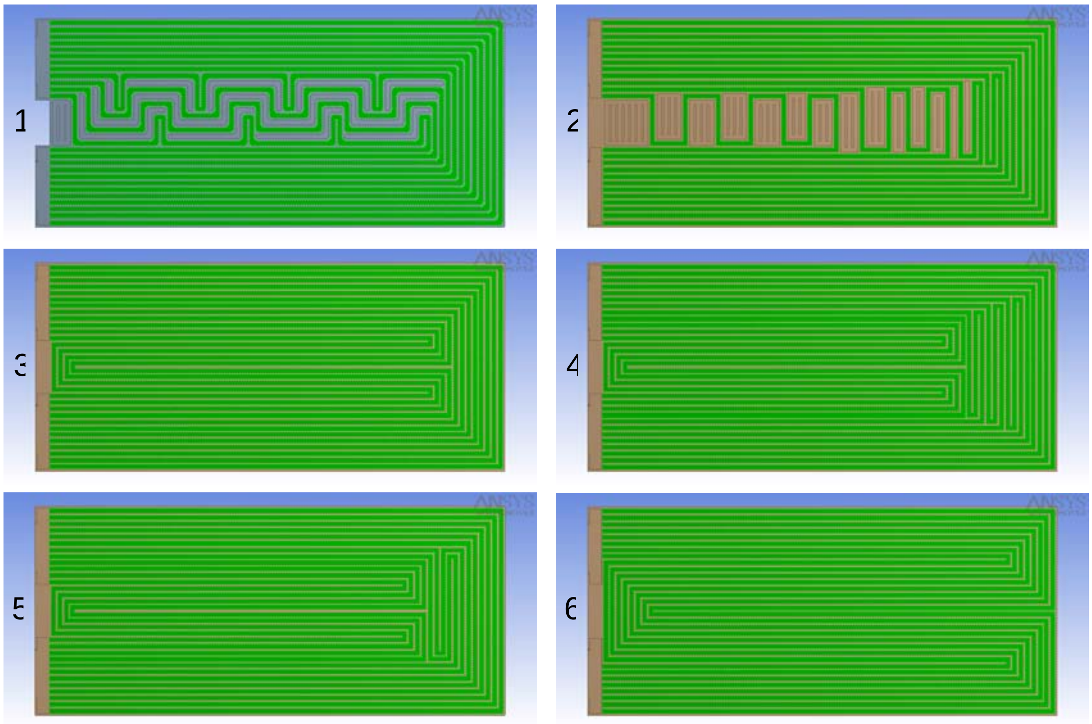


Figure 5.7.2 Variant designs about meandering channel

Table 5.7.2 Design features of variants about meandering channels

Variant	Design feature				Thermal-hydraulic performance	
	Number of channels in “U” shape	Number of channels meandering mainly in toroidal	Number of channels meandering mainly in radial	Blind channels [a]	Maximal temperature in steel, °C	Pressure drop, Pa
1	8	4	0	Yes	589	29,483
2	8	4	0	Yes	629	26,287
3	8	0	4	No	553	27,584
4	5	3	4	No	552	30,333
5	6	2	4	No	549	29,427
6	0	0	8	No	543	99,824

[a] In variant 1 and 2, the flow channels can not cover the whole area of plate. Then some blind channels without flow in them are designed to make

concaves in the steel only for fabrication considerations. Thermal analyses manifest that those blind channels could result in some hot pots in the temperature distribution.

According to Table 5.7.2, the variants of 3rd through 6th without blind channels have better cooling efficiency than the first two designs featured in blind channels. The arrangement about some channels in “U” shape is also a successful design, because the pressure drop is decreased dramatically by using this idea. The deduction is clear because the pressure drop of the 6th variant, with all channels meandering in the same way, and without any ones in “U” shape, is more than 3 times of those of the other five designs. Therefore the 5th variant is selected as the reference design after comprehensive considerations in view of thermal-hydraulics.

5.7.3 Sensitivity of the boundary between BU and stiffening girds

The boundary between the BU and the stiffening grids can be referred to Figure 7.6.1, which shows the situation after the BU is inserted into the blanket box. According to section 5.5, a uniformed convection boundary condition between the BU and the stiffening grids is assumed in the analyses, because most contacts of BU/grid are beryllium/steel interfaces. However a small percent of them are steel/steel contacts, which exist between the breeder wrapper, a thin steel layer, and the grid in poloidal-radial direction. The slight difference on the border can be discriminated in sensitivity analyses. If the real situation is imagined in the BU in normal operations, a very thin helium layer might be formed between the wrapper and the grid, which is not benefit to heat transferring.

Therefore an additional helium layer with different thicknesses is adhered to the surface of the wrapper to understand the influence on the temperature distribution due to the change of the boundary. In the model for the sensitivity analyses, the convection in the thin helium layer should not be prominent thus is ignored, but the heat conduction is considered and is modeled by an assumption of HTC, α_{He}, with an ambient temperature of 450 °C. α_{He} is governed by the following formula.

$$\alpha_{He} = \frac{k_{He}}{l_{He}},$$

where, k_{He} is the helium conductivity, about 0.2793 W/m/K at 450 °C, l_{He} the thickness of helium layer.

The other boundary conditions for the BU model are the same as stated in section 5.5. Table 5.7.3 summarizes the results about the temperature controls in the breeder, the cooling plate and the wrapper with a various thickness of helium layer.

Table 5.7.3 Influence on temperatures due to helium layer between BU and stiffening grids

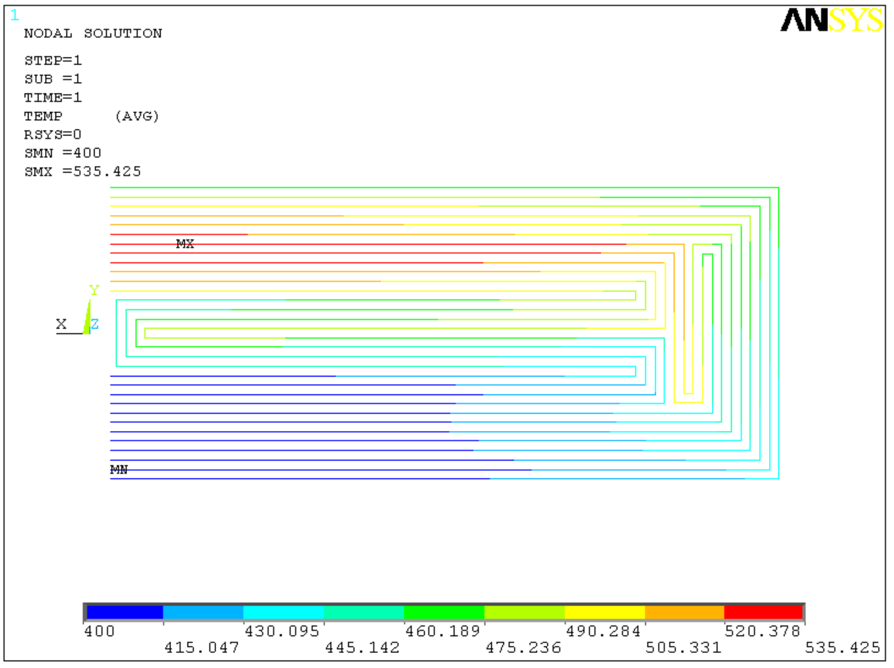
Thickness, $\times 10^{-3}$m	HTC, $W/m^2/K$	Max. temperature in breeder, °C	Max. temperature in cooling plate, °C	Max. temperature in wrapper, °C
∞ [a]	0	865.6	549.7	581.6
1.0	279	865.6	549.7	559.9
0.65	430	865.6	549.7	549.9
0.5	559	865.6	549.7	542.9
0.1	2793	865.6	549.6	529.7 [d]
0.0698 [b]	4000	865.6	549.6	529.4 [d]
0.05	5586	865.6	549.6	529.3 [d]
0 [c]	∞	865.6	549.6	528.7 [d]

[a] This extreme case is corresponding to an adiabatic boundary, which never takes place in reality.
[b] The configuration is equivalent to boundary setting described in section 5.5.
[c] This corresponds to a perfect steel/steel contact in ideal case.
[d] The wrapper includes two stretches in radial direction, which are neighboring to the stiffening grids, and one in toroidal direction, which is buried between breeder bed and beryllium bed. This peak temperature point locates in the toroidal stretch, which is not influenced seriously by the change of wrapper/grid boundary on the other two stretches.

Table 5.7.3 tells the fact that the pebble bed temperature and the cooling plate temperature are not sensitive to the change about the wrapper/grid boundary. However, the design assumption about the EUROFER temperature limit of 550 °C could be broken for the wrapper if the gap between the BU and the grids exceeds 0.65 mm. It is because the heat transferring condition is deteriorated owing to the gap.

5.7.4 Helium outlet temperatures

The helium outlet temperature is designed as 500 °C in the DEMO fusion reactor. Actually the outlet temperatures for different channels could not be uniform completely. They could vary in a scope of, e.g. 470 – 536 °C, according to Figure 5.7.4 as a calculation result for the reference case, because every channel has different thermal-hydraulic condition. However it is possible in future work to have an outlet temperature distribution with a less oscillation amplitude, by means of controlling the mass flow rates exactly by changing the cross sections of the channels or adding orifices. A further optimization should be done to check if the proposed measure could lead to additional prices for an increase of pressure drop and for a more complicated fabrication procedure.



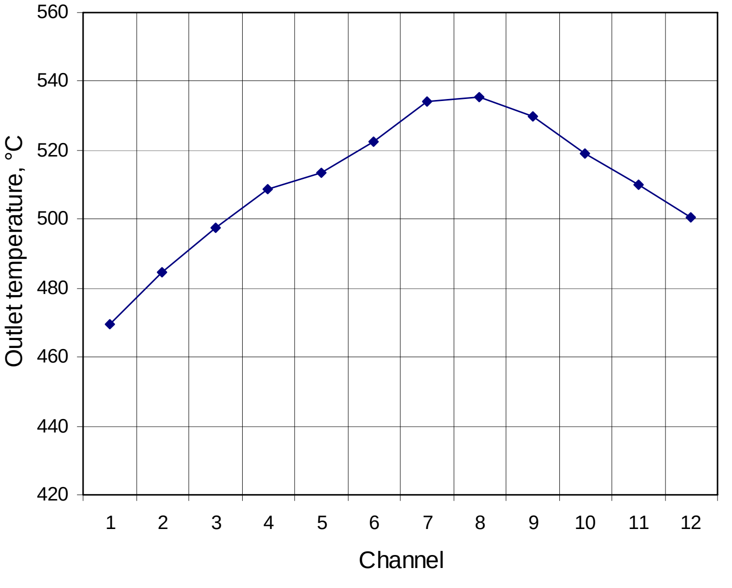


Figure 5.7.4 Helium outlet temperature distribution

6 Structural analyses

6.1 Motives

The structural performance of the BU in thermal state based on the reference design is evaluated by using an FE model. Thermal-mechanical modeling of pebble beds is beyond the scope of this work, therefore only the steel structures in the BU are modeled mechanically. In the BU, a breeder pebble bed is basically confined by a container formed by two cooling plates and a wrapper, which are welded together. Considering the symmetry of the system, a one eighth simplified model of BU is set up and the stress analyses have been done in thermal or operating state.

6.2 Simplified model

It is not necessary to make a whole model of the BU because of the structural symmetry in poloidal direction and the approximately symmetric distribution of temperature in thermal state, referring to Figure 5.6.2. Thus one eighth of the BU including half of the breeder container, i.e., one cooling plate and half height of the wrapper, is modeled. The attached beryllium pebble bed and breeder pebble bed, both in half heights in poloidal direction, are also modeled only for the solution of thermal-hydraulic analysis about the temperature distribution in the model, which is inputted into the mechanical model as a thermal boundary condition. The simplified model and the mesh with about 110,000 nodes are shown in Figure 6.2.1.

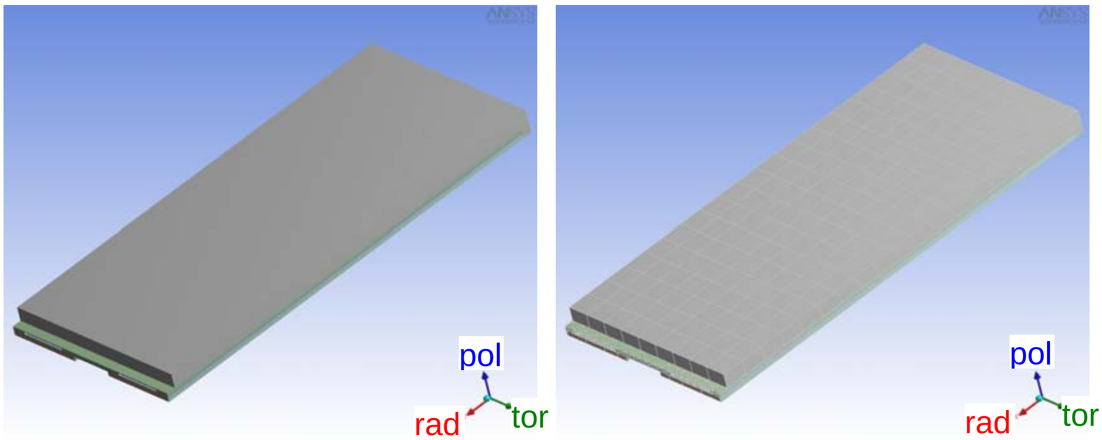


Figure 6.2.1 Simplified model for structural analyses

6.3 Boundary conditions

6.3.1 Thermal boundaries

A complete thermal-hydraulic simulation based on the simplified model is conducted at the first step, in which both the spatially varying heat power modeling obtained by neutronics analysis and the fluid model of the coolant in the steel plate are applied. The temperature field in the model is obtained by the thermal-hydraulic analysis, as shown in Figure 6.3.1. Obviously, on the lower temperature side must be the inlet of helium, and on the other side with higher temperature be the coolant outlet. This distribution is used as a thermal boundary condition for the further mechanics analysis in next step.

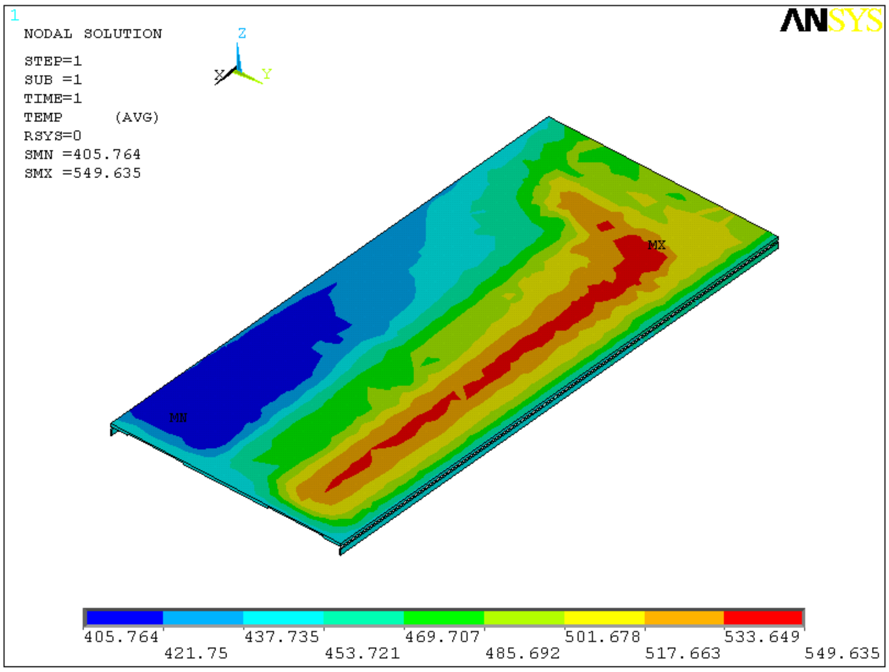


Figure 6.3.1 Temperature distribution in cooling plate and wrapper

6.3.2 Mechanical boundaries

As shown in Figure 6.3.2, four mechanical boundary conditions are specified in the model.

- Pressure load. One of the primary mechanical loads of the cooling plate is the internal pressure of 8 MPa in the coolant channels.

- Symmetry boundary in poloidal direction. At the symmetric plane cutting through the middle height of the wrapper, the poloidal displacement of the plane is given as 0, as a symmetric condition.

The structure would be in reality mounted on the back plate and positioned by the stiffening grids, which supply radial and toroidal constraints respectively. Therefore two directional displacements are assumed at certain points at the rear side of the model.

- Given displacement in toroidal direction. One corner of the cooling plate neighboring to the stiffening grid is fixed in toroidal direction.

- Given displacement in radial direction. Another point in the middle part of the cooling plate attached to the back plate is fixed in radial direction.

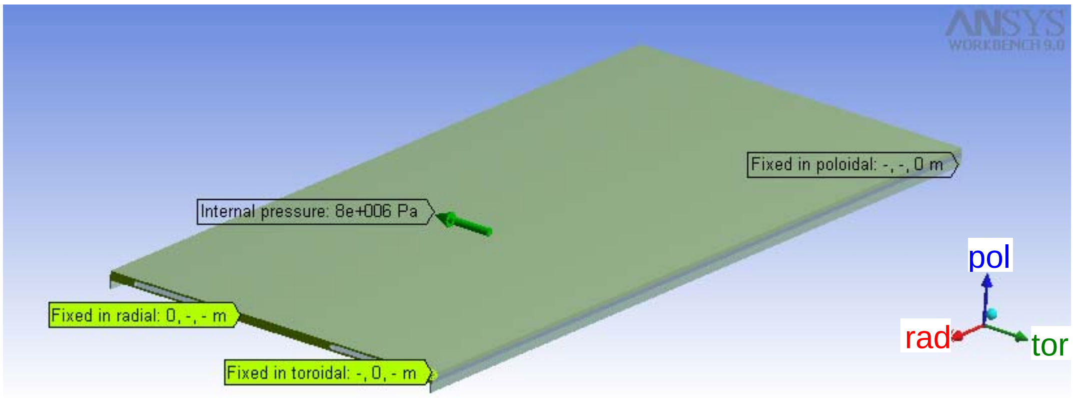


Figure 6.3.2 Mechanical boundary conditions

6.4 Simulation results

The steel structure has to withstand the mechanical stresses and deformations primarily caused by the internal high pressure and the heterogeneous temperature distribution in it. The equivalent von Mises stress, including primary and secondary stresses, is obtained by the FE analysis. The equivalent stress distributions in the cooling plate and the wrapper are shown in Figure 6.4.1 and Figure 6.4.2 respectively. According to the figures, the maximal von Mises stress in the steel is about 220 MPa. If the first criterion about thermal stress limitation, 3Sm rule, is applied, this peak stress is below 3Sm, which is about 351 MPa for EUROFER steel at temperature of 550 °C.

The total and directional deformations in the cooling plate are depicted in Figure 6.4.3 through Figure 6.4.5. About 2.9 mm of total displacement appears in the plate owing to the pressure and thermal loads, as shown in Figure 6.4.3. This deformation mainly distributes on radial and toroidal directions. The displacement in poloidal direction is in an order of 10^{-4} m and then is not presented here as a picture. Figure 6.4.4 shows the radial extension due to the thermal expansion of the plate itself and the overall pushing effect of the internal pressure. By the way, the Cartesian coordinate directions should be clarified while reading the color index in Figure 6.4.4 and Figure 6.4.5. For an instance, the maximal deformation in radial direction is about 2.8 mm, as shown in Figure 6.4.4, which takes place at the front side, i.e. plasma side, of the plate. Figure 6.4.5 depicts the bending effect in toroidal direction due to the feature of the "two-side" distribution of temperature, referring to Figure 6.3.1. The maximal toroidal displacement of about 1.8 mm would make a push to the neighboring stiffening grid. The resulted additional stress can be analyzed in a bigger model including both the BU and the stiffening grids. The deformation of the wrapper is very similar to that of the plate, certainly because they are welded together. So the picture about the wrapper deformation is not shown here.

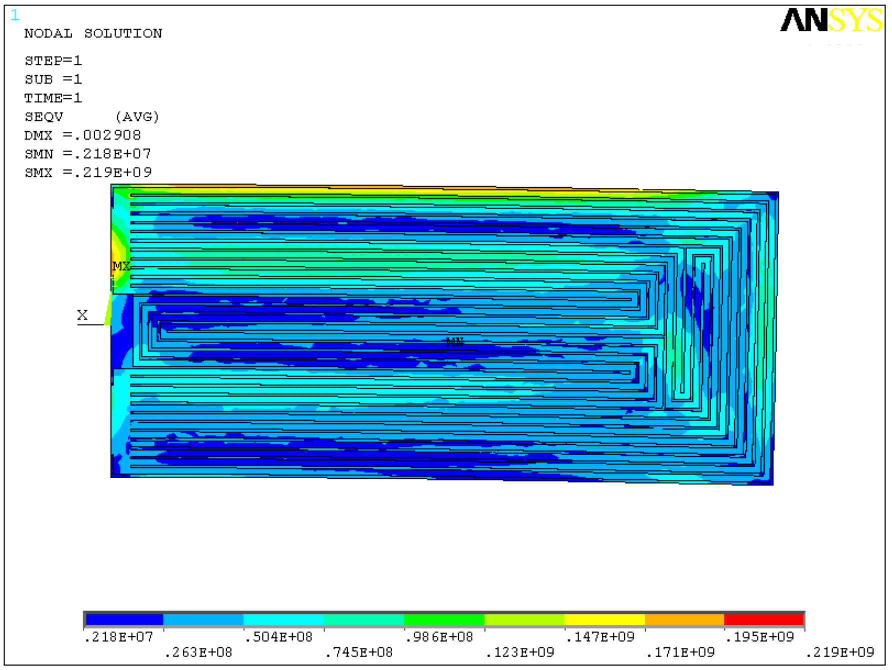


Figure 6.4.1 Equivalent stress distribution in cooling plate

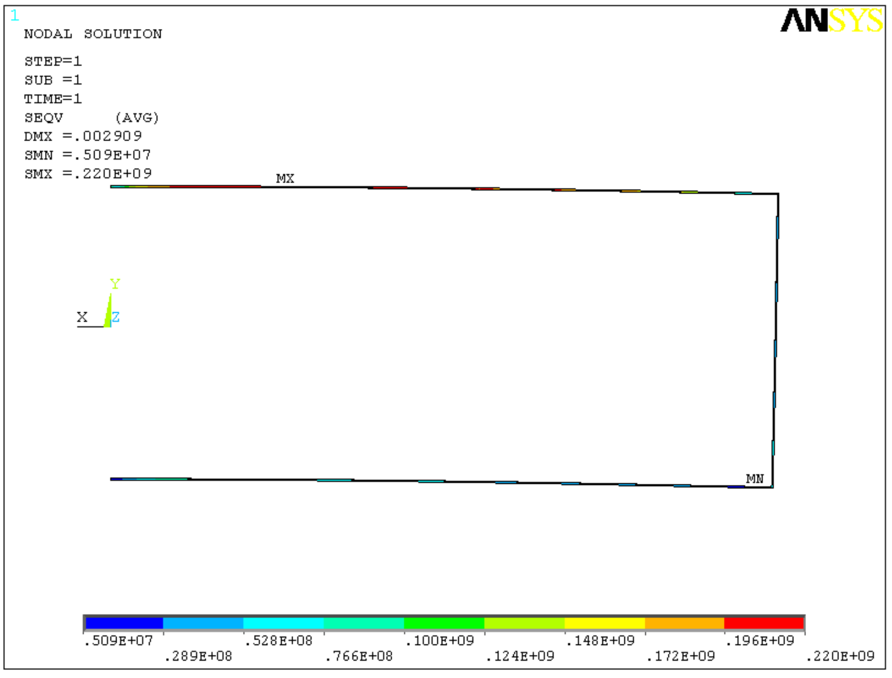


Figure 6.4.2 Equivalent stress distribution in wrapper

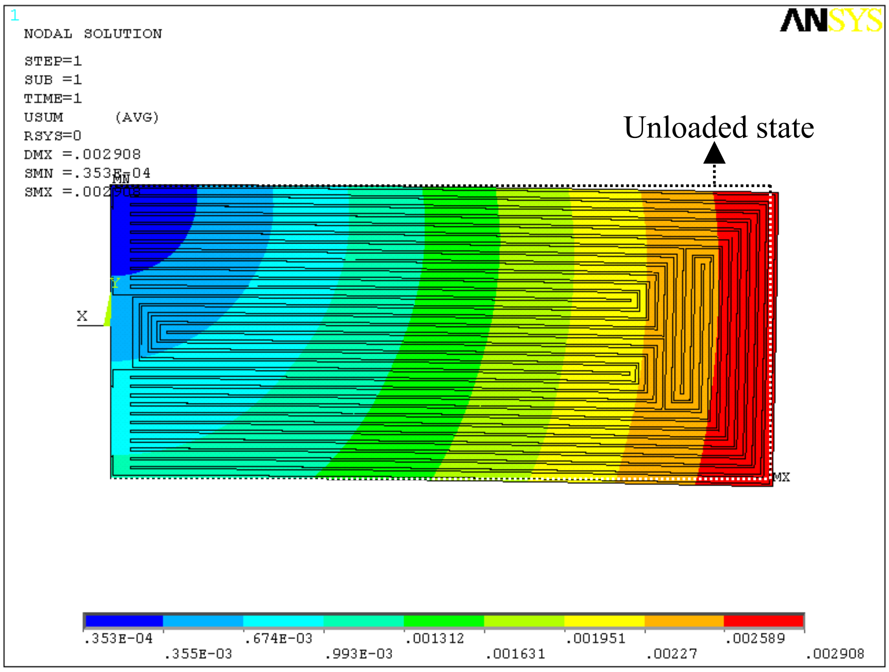


Figure 6.4.3 Overall deformation in cooling plate

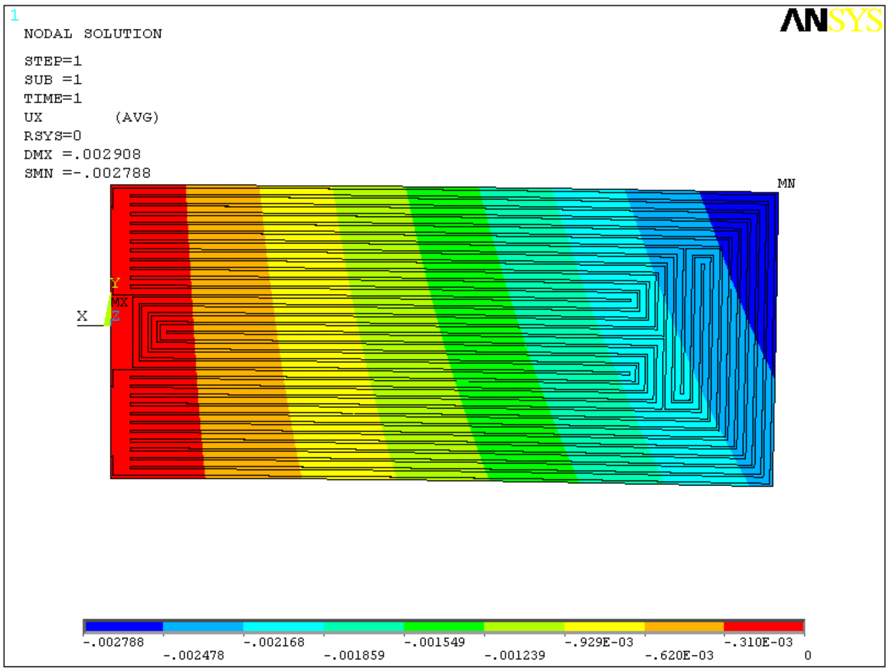


Figure 6.4.4 Radial displacement in cooling plate

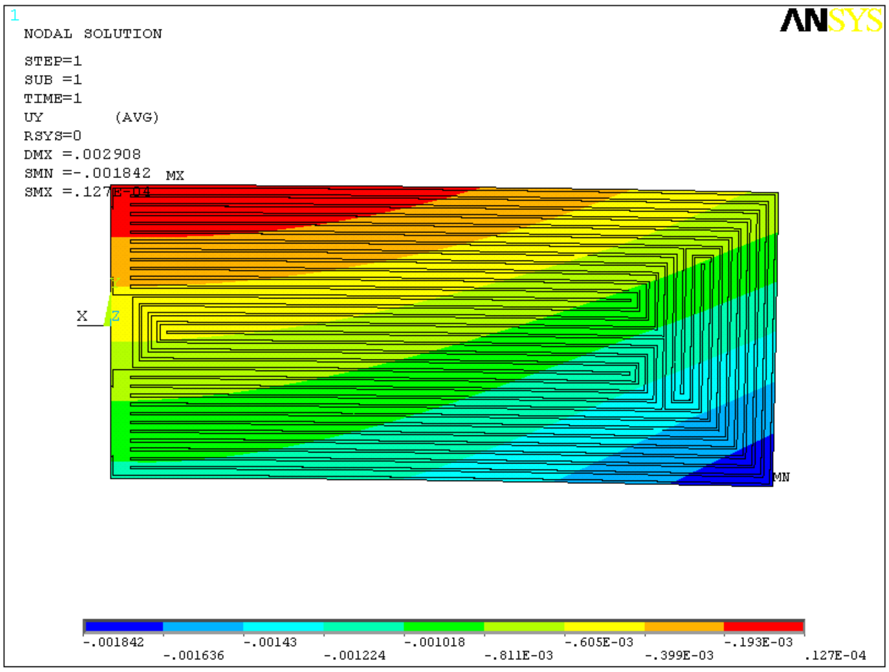


Figure 6.4.5 Toroidal displacement of cooling plate

6.5 Summary of structural analyses

The simulations conclude that the BU design is supported by the structural analyses with the BU model under operating conditions. First, the observed maximal equivalent stress in EUROFER steel including both the cooling plates and the wrapper is 220 MPa, which satisfies the first criterion for thermal stress limitations. It is regarded sufficient to check only the first criterion in the conceptual design analyses for DEMO. Second, the maximal displacement of the structure obtained in the simulations is 2.9 mm, about 0.6% of the BU length in radial direction. This deformation can be looked in an acceptable range from point view of engineering, and would not bring troubles even in the integrated environment of the blanket box in normal operations.

7 Fabrication definitions

7.1 Motives

All parts of BU except the pebble beds are made in EUROFER steel. This section discusses the manufacturing sequences basing on the available techniques in industry. It demonstrates the feasibility of the proposed concept. The new designed HCPB BU is cooled by flat plates with meandering coolant channels. This concept is similar to that of Helium Cooled Lithium Lead (HCLL) blanket concept. It is another European reference for DEMO breeding blankets. Thus the fabrication definitions for HCPB

BU are wished to be helpful to establish a European standard of helium cooled plates for both applications in the HCPB and HCLL BUs caused by their common features.

7.2 Cooling plates

The BU cooling plates are produced by the connection of two symmetric half plates with meandering grooves. The grooves form the cooling channels after connection. Only such a procedure enables the production of cooling plates with the necessary internal cooling channel system. The manufacturing sequence of the cooling plates consists of three steps. First, rolled EUROFER steel tins are ordered completely free of laminations. Rectangular plates with approximately final dimensions of the later cooling plate are cut out of these tins. Secondly, two of such half cooling plates with milled grooves are connected to form one cooling plate by a diffusion weld process (DWP). In the third step, the cooling plates undergo post welding heat treatments and quality examinations. Predefined leak and pressure tests are performed as non-destructive examinations; destructive tests like tensile and Charpy impact yield quantitative results.

7.2.1 Half cooling plates

The goal of the first step is to produce the fitting half cooling plates. Rectangular pieces are cut out of a large EUROFER tin as already rolled. A milling machine is used to plane the half plate at first. Then the meandering concavities are produced in a second milling process as half channels. The engineering drawing about the half plate is shown in Figure 7.2.1 as the reference design defined in section 5.2. It is worth to mention that the cross section of the half channel before DWP is dimensioned by a height of 1.35 mm, which is 4% higher than half of the designed channel height of 2.6 mm. The extra size is used to compensate the local bonding deformations caused by creep and plastic effects during DWP. The pitch between every two channels is 6.5 mm.

A 4.5 mm carbide cutting tool is adopted with cooling medium in processes, to produce the half channels and manifold inlet and outlet. All internal corners in the half plate are milled in a shape with an external radius of 4.25 mm and an internal radius of 2.25 mm.

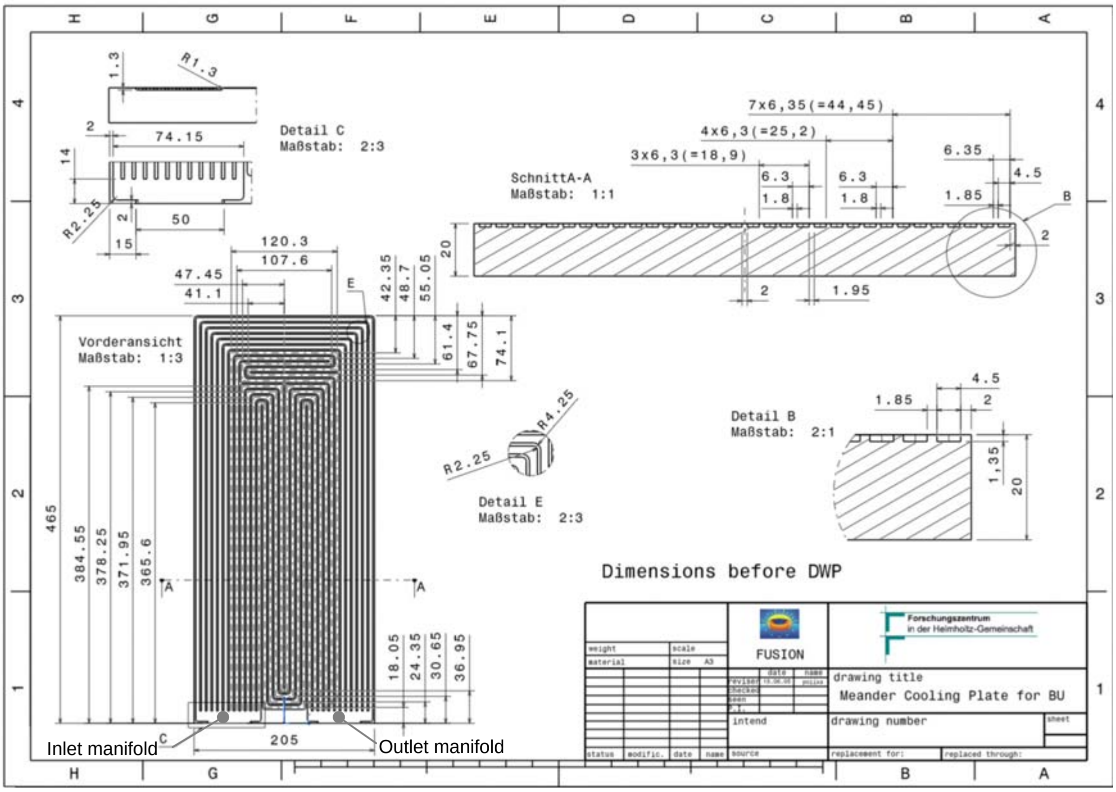


Figure 7.2.1 Engineering drawing of meander cooling plate

7.2.2 Diffusion welding process

– Pre-processing for DWP

In order to guarantee an equalized bonding pressure in the weld area, the thickness of the raw half plate is defined as 20 mm in the current design for a 1:1 mock-up, although the final plate thickness is designed as only 5 mm. The thickness of the raw material can be reduced for mass production. The welding planes of both plates must be, before DWP, in a very high quality with a tolerance of 0.01 mm in parallel. A prescribed surface roughness about 0.2 µm must be realized. The bonding areas need a thorough clean surface. It has to be manufactured by a high speed dry milling process. Any additional cooling medium is not allowed avoiding unclear contaminations on the bonding surface. In order to protect the channel structure from any possible damages owing to the high speed milling, the plate is positioned additionally by steel stripes in dimension of 1.4×4.5 mm^2, besides general fixings. After milling the plate material is kept in an evacuated foil to avoid any further contacts. Right before the DWP a 10 minute cleaning procedure with 38 °C acetone in an ultrasonic bath is repeated four times. In the diagonal corners of the plate two holes in diameter 3 – 4 mm are made to guarantee a precise positioning of the bonding zone.

– DWP

The present technique of the uniaxial diffusion welding supplies a two-step DWP. The parameters for the first step include a bonding pressure of 18 MPa, a temperature of 1010 °C and a processing time of one hour imposed by the plastic and creep mechanisms occurring in the DWP. The second step with a processing duration of 5000 seconds applies diffusion process as a major driving force to weld. The adopted two-step DWP has a big advantage of a less compression of the work pieces, about 4%, than that of one-step DWP, about 10%. However the process parameters have not been verified for the 1:1 mock-up. The research to gain them is still being conducted currently. Additional parameters of DWP are presented in [16]. To ensure an overall specific constant bonding pressure for the whole channel duct structure, the pitch of duct and channels is dimensioned equidistant as far as possible. The dimension tolerances in the range of a few ±0.1 mm are acceptable for DWP.

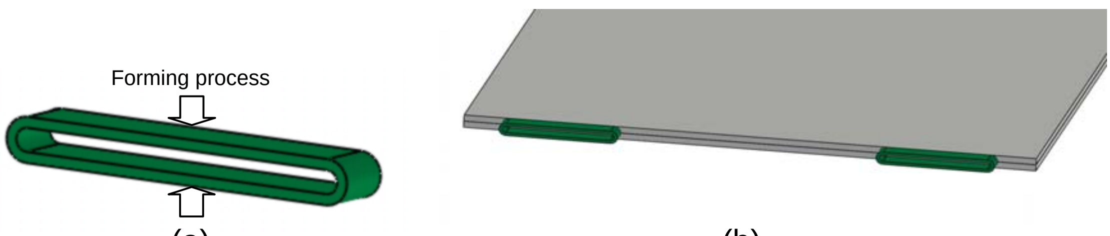
– Post-processing of DWP

The welded plate is reduced in thickness to a final dimension of 5 mm from both sides by milling processes or spark erosion procedures. The openings to the manifold volumes, two long holes in total length of 50 mm and a radius of 1.3 mm are also milled in this stage, which supply connections to helium headers/collectors. The final lateral dimension can be reached by the same procedures.

7.2.3 Helium headers and collectors

Helium header and collectors are basically long-hole pipes, as shown in Figure 7.2.3 (a). A round pipe is produced at first by turning, which external perimeter is the same as that of the expected long-hole pipe. Then a forming process is applied to form the round pipe into a long-hole pipe until the thickness reaching the cooling plate thickness of 5 mm, as mentioned in section 7.2.2. On the other hand, the pipe is produced longer than the assembly length in order to get a connection for pressure and tightness tests later.

The prepared header and collector then are connected to the cooling plate, as shown in Figure 7.2.3 (b), by a Tungsten Insert Gas (TIG) join with filler wire. The welds have to be ground in a grinding process to the thickness of the cooling plate. A plug joining the long-hole pipe to a round pipe with a diameter of 5 mm allows connection to test conditioning elements.



(a) (b)

Figure 7.2.3 Header/collector of cooling plate

7.2.4 Post welding heat treatment and qualification tests

The complete cooling plates including assembled helium headers and collectors are produced separately. Then a post welding heat treatment (PWHT) is foreseen to be realized with an austenitic temperature of about 980 °C for half an hour and a tempering treatment at temperature of about 730 °C for 3 hours. Further information about PWHT is in [17]. In the end the surface colours formed in the heat treatments have to be eliminated completely with a metal brush cleaning process for further joining operations later.

Then qualification tests, including leak or tightness test and pressure test, are carried out to every single cooling plate. The tightness performance is inspected in a vacuum chamber. In the test the cooling plate is filled with helium in the meandering channels with a pressure of 0.5 – 1.0 MPa. The upper limit of the helium leaking rate is determined as about 10^{-5} mbar l/s. After leak test, pressure test is done in order. Water is selected as the medium for high pressure test with a pressure of 14 MPa. Certainly the water must be removed completely after the test by a drying process with a temperature below 150 °C, which is imposed by avoiding any surface colours possibly generated in the process.

After the tests, the helium headers and collectors with additional sections only for connection to the test elements are cut and ground exactly to the assembly length.

7.3 Purge gas system

Purge gas system is in principle a helium circuit in a low pressure of 0.12 MPa to remove the tritium generated in ceramic and beryllium pebble beds. The reference design consists of purge gas pipes located in the breeding zone, and the manifolds in the structure of the back plate to distribute and collect purge gases. As shown in Figure 7.3.1, the purge pipe is designed as a half round pipe with an internal diameter of 6 mm. The pipe includes two stretches in radial and toroidal directions, respectively. The radial stretch is used to transfer purge gas from the inlet manifold to the plasma side of the pebble beds, the toroidal stretch being drilled a row of small holes with 1 mm diameter is applied to emit the purge gas into the pebble beds through those holes. The purge gas is collected in the outlet manifold in the back plate after it travels from the front side to the rear by permeation through the pebble beds.

The purge pipe is welded onto the cooling plate, as shown in Figure 7.3.1. Two sets of purge pipes are configured for each canister. One set is welded on the side of breeder bed, another on the side of beryllium bed. The purge pipes are joined to the corresponding manifolds in the back plate by tight welding.

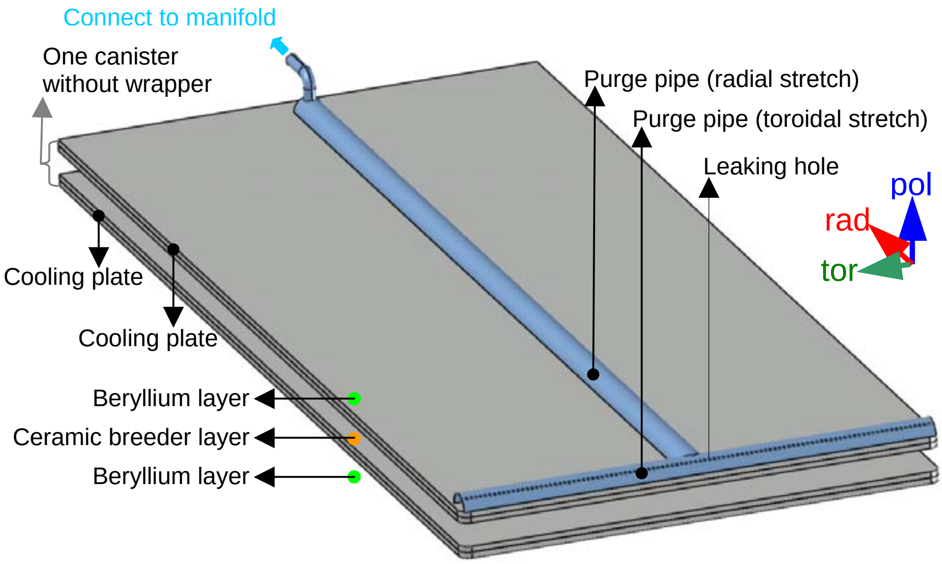


Figure 7.3.1 Purge gas system

An alternative design about purge gas system is under investigation. In this design the purge helium is pumped into the beryllium beds through holes drilled in the BU back plate. The purge gas permeates the beds in radial direction from the rear to the front, where the gas enters the ceramic canister via holes dilled in the stretch of the breeder wrapper at the FW side. Then the purge gas travels in an opposite direction, from the radial front to the rear, by permeating the ceramic beds. A main advantage of the alternative concept is simplifying the design by avoiding pipes inside the beds; further investigation should prove that the breeder wrapper can assure the necessary helium tightness in all operating conditions.

7.4 BU back plate

BU back plate achieves the following functions, (i) to fix the four breeder canisters, (ii) to separate the beryllium pebble bed from the helium manifolds, and (iii) together with stiffening grids and the first wall, to form spaces for beryllium pebble beds. A big advantage of applying the back plate structure is that the number of possible welds is reduced largely while assembling the breeder canisters. In addition the geometrically complicated coolant inlet/outlet manifolds and manifolds for purge gas are built in the back plate. The engineering design about the back plate is shown in Figure 7.4.1.

The back plate is produced out of a 30 mm thick rolled plate material in square dimensions of 205 × 205 mm^2 for the DEMO reactor. The rear and front views of the back plate are shown in Figure 7.4.2 (a) and (b) respectively. The coolant inlet/outlet manifolds and the two purge gas manifolds need pipe connections to the canister with good tightness. To realize the joining process with adjusted material thicknesses, seam lines are expected with milled welding noses, an example as demonstrated in Figure 7.4.2 (c). In order to mount the cooling plates onto the back plate, two long holes are milled for each cooling plate at the radial front of the back plate.

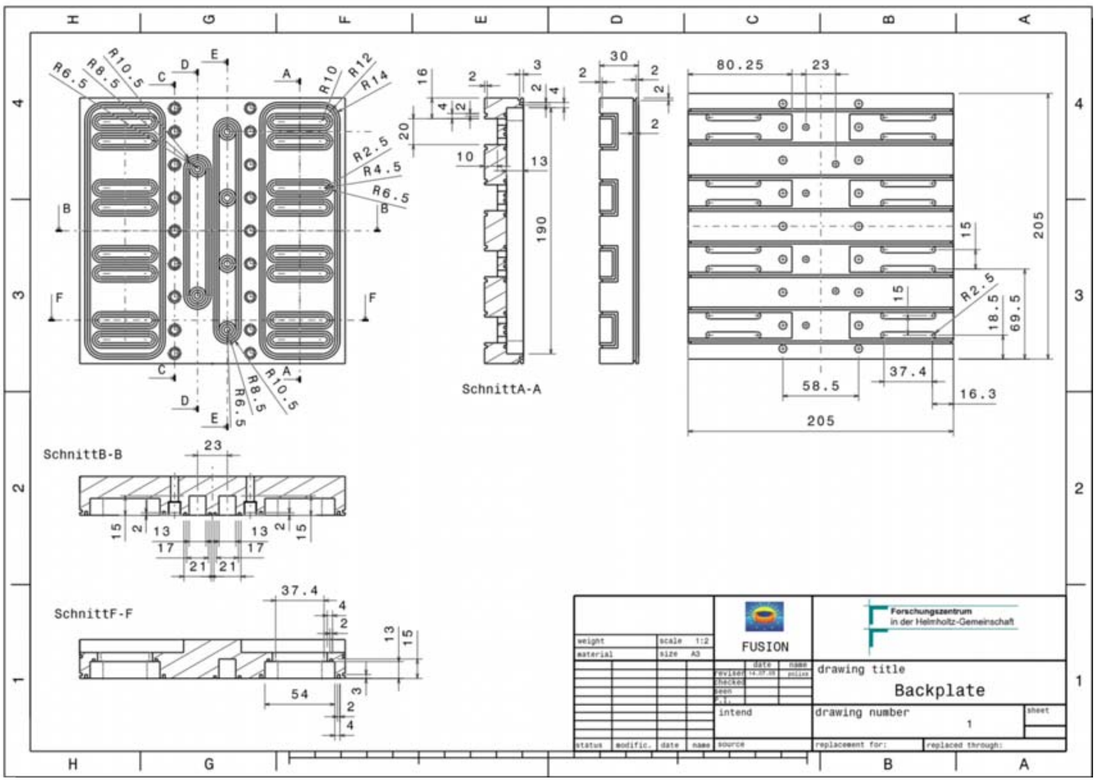
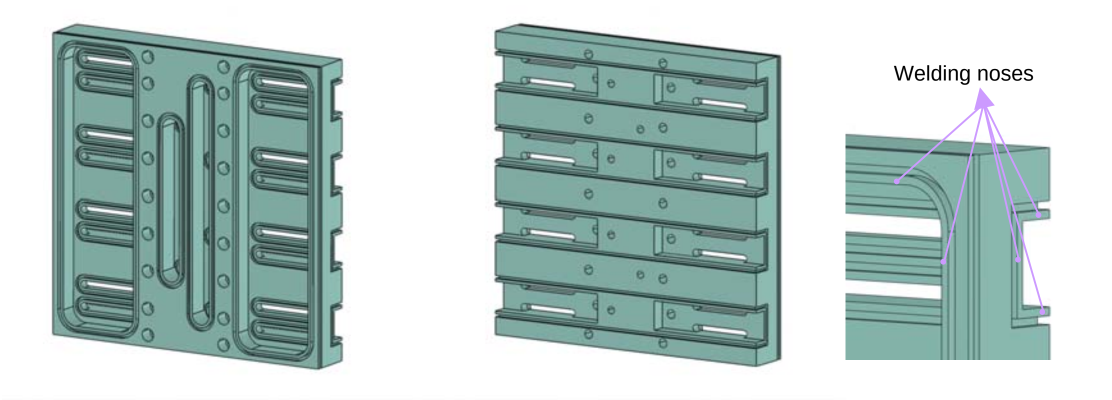


Figure 7.4.1 Engineering drawing of BU back plate



(a) Rear view (b) Front view (c) A detailed view

Figure 7.4.2 Different views of BU back plate

7.5 Accessory parts

– U-formed breeder wrappers

The breeder wrapper is manufactured out of a rolled plate with a thickness of 1.5 mm. After being cut by using a water jet the plate stripe is bent twice in 90°. The toroidal dimension of the wrapper is about 1 mm more than the corresponding width of the cooling plate. The extra sizes including that in thickness of the wrapper are ground off by a grinding process after it is welded together with the cooling plates.

– Cap plates for manifolds

All cap plates closing the manifolds at the rear of the back plate are made out of rolled materials. After milling out the outline dimensions with a half V-seam the holes for connecting the inlet/outlet pipes are drilled in the expected locations with a half V-seam too.

– Additional pipes of BU

All the round pipes for connections to the coolant and purge gas manifolds are produced by turning or deep drawing for mass production, and made out to be attracted and seamless tubes with a slightly longer size in further serial productions. The pipes are adjusted to their functional length only after being joined to the corresponding cap plates.

7.6 Assembly of BU

To realize the assembling of breeder canister two cooling plates are fixed with one U-formed wrapper by tight welding. The surrounding welding noses are fixed to the cooling plates at the same manufacturing step. Then the welding by using TIG translation technique connects the canister to the back plate with tight seams. The assembled BU is demonstrated in Figure 7.6.1.

Before the BU is integrated into the blanket modular, a complete PWHT, leak and pressure tests must be done in sequence for the whole assembled BU. They are similar to what have been done for every single cooling plate as described in section 7.2.4. The process parameters are the same as presented in that section.

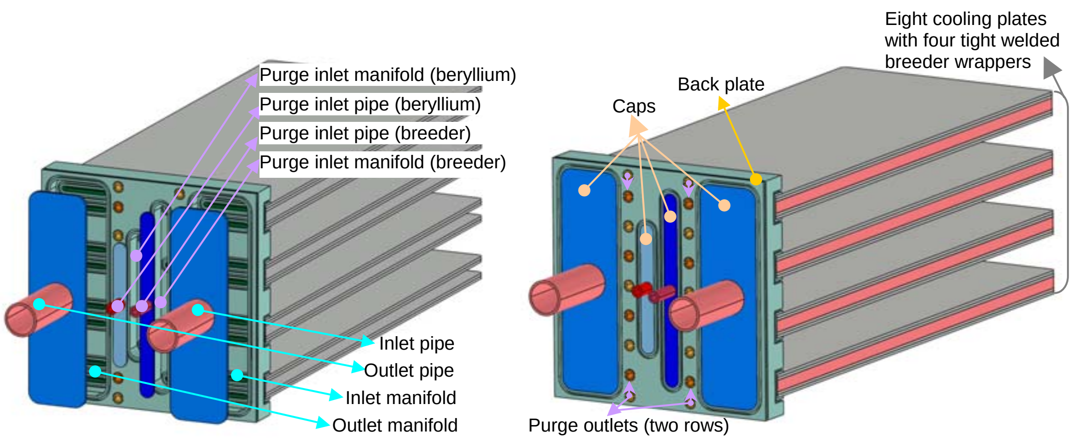


Figure 7.6.1 Assembly of BU

7.7 Integrating BU into blanket box and pebble bed filling

In order to integrate the BU to the stiffening grids successfully, it is expected to adjust every breeder canister and the back plate with a grinding process to a certain grid position, which guarantees the good contact between the breeder canisters and the stiffening grids. With a TIG translation process the surrounding join noses of the back plate get tight contacts to the stiffening grids as shown in Figure 7.7.1.

Two possibilities can be used to fill the pebble bed materials. As shown in Figure 7.7.2, the purge gas outlet equipped with a semi-permeable thread bolt is used to fill the pebble bed materials, before the blanket modular is closed by a bigger back plate for the whole blanket box. Another strategy is to fill after the blanket modular is closed. A specially formed pipe penetrating the cap of the modular box is used as the filling tool. One of the thread bolts as shown in Figure 7.7.2 is used to insert the filling pipe tool. It is certain that a vibration process can make the pebble fillings much easier. The opening on the cap can be closed by welding with laser technique after the fillings are completed. Further detailed information can be obtained by the studies on the real mock-up for the HCPB blanket modular.

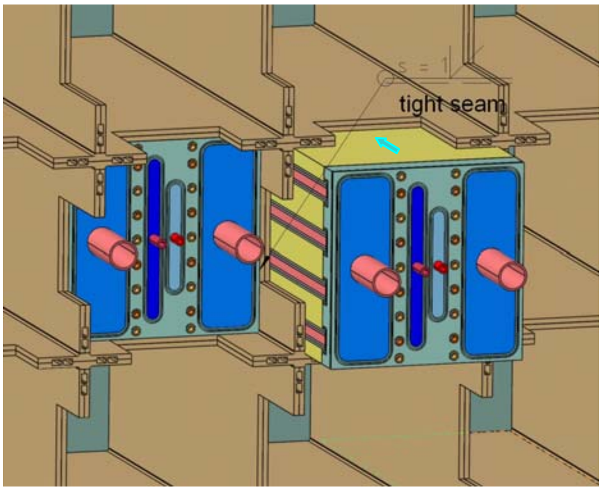


Figure 7.7.1 Assembling BU into stiffening grids

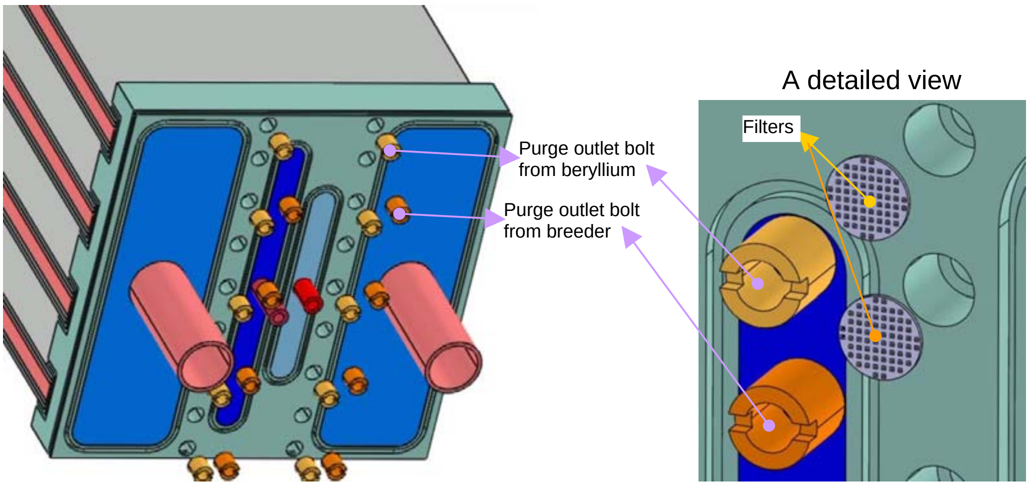


Figure 7.7.2 Disassembled purge outlet thread bolts with BU

8 Conclusions

The new design of HCPB BU for DEMO fusion reactor has been developed for a reference configuration that comprises four breeder pebble beds with a featured 10 mm poloidal height, and beryllium pebble beds. The pebble beds are separated by four thin steel wrappers and four pairs of flat steel plates with internal meandering helium cooling channels. The optimal arrangement of the meandering channels is obtained by optimization analyses that propose six outer channels in "U" shape, two toroidal-meandering channels and four radial-meandering channels. The tritium breeder material considered in this assessment is Li_4SiO_4 with a ^6Li enrichment of 40 at%. The beryllium is used as neutron multiplier, and EUROFER steel as the supporting structural material.

Neutronics analyses based on 3D Monte Carlo simulations show that the new design can reach a TBR of 1.119 with a neutron multiplication factor of 1.65 for a radial length of 460 mm, and that the blanket can supply good shielding for the in-vessel parts against intense neutron irradiations.

Thermal-hydraulics analyses find that, based on the reference design, the temperature peaks in breeder, beryllium and steel under operating conditions are 902 °C, 615 °C and 549 °C respectively, which are inside the design criteria for the temperature of the different functional materials. The maximal temperatures in the ceramic beds are about 900 °C, slightly less than the maximum allowed target of 920 °C, but still sufficient to have a good tritium release from the breeder ceramic. The hydraulic pressure drop of the helium flow in the BU is about 0.029 MPa. The new design with the low pressure loss supplies more space of choices while arranging the in-vessel parts in the DEMO reactor. Thermal calculations indicate that 4.5% of the overall thermal power of one BU is conducted away by the FW, 12 % by the stiffening grids, and the remaining major part of 83.5% by the cooling plates. Sensitivity calculations show that a helium gap between the BU and the stiffening grids up to 0.65 mm can be tolerated without exceeding the temperature design limit of 550 °C.

Stress analyses make conclusions that the maximal thermal stress in the EUROFER structure is about 220 MPa, lower than the value of 3Sm prescribed by the first criterion for thermal stress limitation, and that the overall displacement in the structure does not exceed 0.6% of the radial length of the BU, which is regarded as an acceptable deformation. Therefore it is concluded that the function of the steel structure can be kept in effect without serious mechanical failures and distortions in normal scenario of power operations.

Manufacturing sequences have been defined based on the currently available industrial techniques. First the cooling plate with internal meandering channels is made from two symmetrically manufactured half plates by using a key technique of diffusion welding process. Then the back plate with complicated manifold structures and accessory parts are produced by forming, milling, grinding, drilling, turning, tempering, joining, welding and/or other mechanical production techniques. The following step is to assemble the prepared parts together by using welding or other joining techniques. Especially a technique about Tungsten Insert Gas join and a design about welding noses are adopted to ensure the tight weld or connect where necessary. In the fabrication process, post welding heat treatments defined for martensitic materials are applied for assembled parts after any forming or thermal processes including welding. Finally, the procedures about integrating the BU into blanket modular box and filling the pebble bed materials are outlined.

Especially the purge gas system is designed for BU. Every breeder canister is configured two purge pipes for ceramic bed and beryllium bed, respectively. The purge pipe is feature in a semicircle cross section. The purge gas is transferred through a radial pipe from the manifold to the plasma side of the pebble bed, and is distributed in a toroidal pipe through a dense array of small hole bored on it. The gas is collected at the purge outlet manifold after permeation through the pebble beds. An alternative concept of purge flow has been considered, as well, in which the helium flow is driven into the beryllium beds and returns through the ceramic beds without pipes.

Three aspects are proposed for the work in future.

- The breeder pebble bed height can be increased by a certain number to make the temperature peak of lithium ceramic closer to the limit, for the reason that tritium release is more efficient at even a little higher temperature.

- In order to make uniform the helium outlet temperatures of the meandering channels, proper cross sections or block ratios of the channels can be designed. It is also helpful to flatten the temperature distributions in the steel plates.

- A sufficiently precise thermal-mechanical model about pebble beds are highly desired in order to improve the accuracy of numerical modeling.

The three aspects together with the choice between the two purge systems will be further investigated in the frame of the HCPB TBM design activities.

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