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Abstract

Next-step fusion nuclear devices require plasma-facing components that can survive a much higher neutron dose than ITER, and in many design concepts also require higher operating temperatures, higher reliability, and materials with more attractive safety and environmental characteristics. In search of first wall concepts that can withstand surface heat fluxes beyond 2 MW/m^2, we analyzed advanced "monoblock" designs using coolants and materials that offer more attractive long-term performance. These use tungsten armor and heat sinks, similar to previous designs, but replace the coolant with helium and the coolant containment pipe with either low-activation ferritic-martensitic steel or SiC/SiC composite. The results of analysis show that helium-cooled steel can remove up to 5 MW/m^2 of steady-state surface heat flux and helium-cooled SiC/SiC can remove nearly 10 MW/m^2 while satisfying all materials and design requirements. This suggests that a He-cooled W/SiC monoblock could withstand divertor-like heat fluxes.

1. Introduction and background

Previous conceptual designs of tokamak fusion power plants predict very modest average surface heat fluxes of the order of 0.25 MW/m^2 [1]. The "intermediate mission" FNSF design point currently under investigation has an average value of 0.20 MW/m^2 [2]. Peaking factors related to nonuniformity of radiation from the core are typically in the range of only 1.25. In previous power plant studies, a sufficiently thick scrape-off layer was assumed to prevent contact of plasma with the first wall (FW), and plasma startup was achieved without creating high localized heat fluxes on the wall. Fast transients were considered, such as ELM's and disruptions [3], but these affect only a thin layer of the order of 100 μm and do not impact the gross thermal and mechanical behavior of plasma facing components. With these low values of steady-state heat flux, relatively simple design solutions exist, such as the EU Demo "segment box" first wall concept [4].

For FNSF, a more conservative approach was adopted. Plasma startup may create locally higher heat fluxes, and long-term transients (with time scales of the order of seconds) are considered in the design. Components capable of withstanding heat fluxes exceeding 2 MW/m^2 over time scales exceeding the thermal time constant of the first wall are desired. Previous attempts to modify the conventional first wall design were successful at achieving steady-state heat flux handling capablility up to 2 MW/m^2 in conceptual studies using W pins embedded in an advanced, nanostructured ferritic alloy plate bonded onto the conventional ferritic-martensitic steel cooling channels [5]. Similar to most He-cooled first wall designs, roughening was applied to the coolant channel (front surface only) to enhance heat transfer and achieve acceptable pressure drop.

The monoblock concept provides the possibility of even higher heat flux capability, in part due to the spreading of heat over a larger coolant surface area. Figure 1 shows an example of a monoblock cooling channel to be used in ITER, including an internal swirl tube to enhance heat transfer in water. The high-conductivity W blocks conduct heat deeper into the wall, utilizing the sides of the cooling channels as well as the front surface. The initial goal of the present study was roughly a doubling of the achievable heat flux, to the range of 4 MW/m^2, primarily by finding an optimum geometry that allows heat to penetrate into the largest possible cooling channel area.

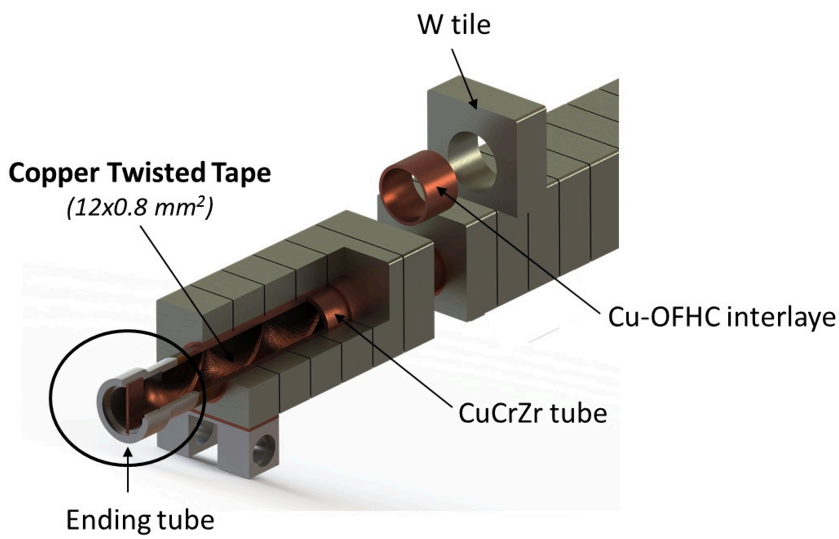


Fig. 1. ITER monoblock divertor

Following its adoption in the ITER project, the monoblock divertor concept has received a great deal of attention in recent years. Significant R&D have been performed on a monoblock concept using water coolant inside a copper alloy pipe with W armor blocks [6]. The ITER qualification program seeks to demonstrate performance as high as 20 MW/m^2 including cyclic operation corresponding with the expected service life in ITER. As a result of interest by the ITER team, the performance of W monoblocks is expected to be established for a range of operating conditions including thermal, mechanical and plasma loads.

Due in part to the interest in monoblocks by ITER, it is natural to explore their applications in devices beyond ITER. Already designs have been analyzed for the EU Demo [7] and Korean Demo [8] that use W blocks and water cooling, as did ITER, but low-activation ferritic-martensitic steel (such as Eurofer) for the coolant containment pipe. In both cases, the goal surface heat flux was approximately 10 MW/m^2. The EU Demo design used a compliant Cu interlayer between the steel and W, and found the goal could be achieved without exceeding structure temperature, CHF or ratchetting limits [7]. The K-Demo design used a vanadium interlayer and established the design's ability to meet temperature limits, while stress analysis has yet to be reported. [8]

In this article we consider several variations of advanced monoblock designs, which are described in Section 2. All of the design variations use pure W blocks and He coolant. Water has been avoided for long-term commercial applications due to several issues related to performance, safety and the minimum operating temperature requirement of steel [9]. The containment pipe is either low activation ferritic steel (both conventional ferritic/martensitic and more advanced high-temperature steels were considered) or SiC/SiC composite. With recent advances in the application of SiC composites for both fission [10,11,12] and fusion [13], we considered the use of SiC/SiC as a credible He coolant containment pipe in a time frame consistent with the likely implementation of FNSF within the US.

Two geometric variations were considered: a circular pipe similar to the ITER divertor monoblock or an elongated rectangular duct, similar to a microchannel array. The analysis is performed parametrically in order to determine the optimum design details. Variables include physical properties, geometric dimensions and coolant conditions. The method and results are presented in Section 3.

These advanced monoblock concepts push the "state of the art" in order to reap the benefits of improved performance as well as safety and environmental attractiveness that factor heavily in the US strategy for fusion development as a future competitive future energy source. As a result, R&D needs remain in the areas of materials development, fabrication and joining, and high-fluence radiation damage effects. These are summarized in Section 4.

2. Design concepts

2.1 Materials and properties

A typical monoblock design consists of four types of materials with different functions: a plasma facing material (or armor) resistant to plasma interactions, a high conductivity heat sink material, a structural (or "pressure vessel") material to contain the coolant and provide mechanical strength, and interlayer materials between the pressure vessel and heat sink to provide acceptable heat transfer and structural integrity.

Similar to ITER and some Demo designs, we adopted tungsten as our preferred plasma-facing material. Its high thermal conductivity allows it to fulfill the role of heat sink as well. Its advantages include its refractory nature, low plasma sputtering rate, high strength, high thermal conductivity and acceptable neutron activation, while its brittleness is the main drawback that impacts its use as a candidate structural material [14]. The maximum allowable temperature of 1300˚C is determined by recrystallization and loss of creep strength. The lower bound to maintain ductility under irradiation is uncertain, but probably in the range of 700-800˚C. In the steel monoblock designs we examined, it is not possible to maintain the armor above the ductile-to-brittle transition temperature, so no lower limit was imposed. Although the armor serves no structural or pressure vessel functions, still it must exibit sufficient crack resistance to allow efficient heat transfer and to prevent spallation of material into the vacuum chamber.

Uncertainties remain in the use of tungsten as an armor, but a substantial R&D program is underway to validate the material in ITER and Demo environments [15].

The structural material is a critical part of the design, since it has a structural and pressure containing function as well as the requirement to conduct heat efficiently into the coolant channels. For a water-cooled divertor, low-activation ferritic/martensitic (FM) steel (such as Eurofer) and CuCrZr have been studied as the coolant containment pipe materials [7,14]. According to [14], the operating temperature window of Eurofer is from 325 to 550 ˚C. Again, the upper temperature is limited by creep strength. More advanced high-temperature steels (such as ODS steels) can raise the upper limit to 650 ˚C. The conventional assumption of the lower limit of FM steels is 350 ˚C. However, post-irradiation annealing of defects will result in a residual shift in DBTT of only 48 ˚C. It provides the possibility to use Eurofer at a lower temperature, like 325 ˚C.

Besides low-activation ferritic steels, SiC/SiC composite was also considered as a candidate for the He coolant containment pipe. SiC/SiC composites have been under development as a high temperature structural material for both fission and fusion applications. Its operating temperature window was assumed to be from 400 ˚C to 1000 ˚C. The upper limit is determined by void swelling considerations while the lower limit is due to thermal conductivity degradation concerns. Other thermo-mechanical properties for the simulation were obtained from [13].

Major material properties of coolant containment pipe materials (low-activation ferritic steels and SiC/SiC composite) and plasma facing component material (tungsten) used in the FE model are summarized in Table 1. Most of properties are temperature-dependent. But for those with only minor changes when the temperature varies within the operating temperature window, the average values were used in simulations. For SiC composites, the effect of neutron radiation on thermal conductivity was taken into account.

Table 1
Summary of material properties

	Thermal conductivity (W/mK)	Thermal expansion coefficient ($\times 10^{-6}$ K^{-1})	Heat capacity (J/kgK)	Young's Modulus (GPa)	Operating temperature (℃)
Steel	~26	~10	~550	~210	325-550/650
SiC/SiC	15-8 (500-1000 ℃)	4-5 (400-1000 ℃)	1070-1260 (400-1000 ℃)	~200	400-1000
Tungsten	145-113 (RT-1000 ℃)	~4.5	~148	360-240 (RT-1000 ℃)	500-1300

In this study, a compliant interlayer was considered between the armor and the structural material to compensate differences in thermal expansion coefficient. A key characteristic that the interlayer material should have is a thermal expansion coefficient between the two adjacent materials. Thus, vanadium is a promising candidate between steel and tungsten, as suggested in the K-Demo divertor design [8]. Its thickness was assumed to be 0.2 mm. Since the thermal expansion coefficient of SiC/SiC composite and W are very close to each other, only a joining material (*e.g.* a braze) is needed, with a thickness so small that the effects on thermal and mechanical behavior were neglected.

At the level of preliminary design, only low temperature design rules, without considering creep and fatigue interaction, were applied. Thus the $3S_m$ rule was used to check for failure. For the low-activation ferritic steels, the allowable stress intensity ($3S_m$) is around 450 MPa (with minor variations with respect to temperature change) at the operating temperature. The stress limits of SiC/SiC were discussed in the ARIES-I study; recommended maximum primary and secondary stress limits were 140 MPa and 190 MPa respectively [16]. Since tungsten is not considered a structural material for our designs, the $3S_m$ design criteria was not applied to it. However, to prevent cracks in tungsten, we assumed that the maximum stress should be less than the ultimate tensile strength, which is strongly dependent on the temperature: 1000 MPa at 500˚C and 600 MPa at 1000 ˚C.

2.2 Configurations

A circular pipe is commonly used in divertor monoblock designs (like those for ITER and Demo). Besides this conventional design, an elongated rectangular duct with rounded corner, similar to a microchannel heat sink, was also considered in this study. Microchannel arrays have been shown to offer solutions to thermal dissipation problems, such as cooling of micro-electronics. By comparing the results of these two configurations, the added performance of the microchannel geometry was clearly shown in Section 3. Both of these geometries are depicted in Figure 2. Models in the simulation are in 3D with a thickness of 4 mm in the axial direction.

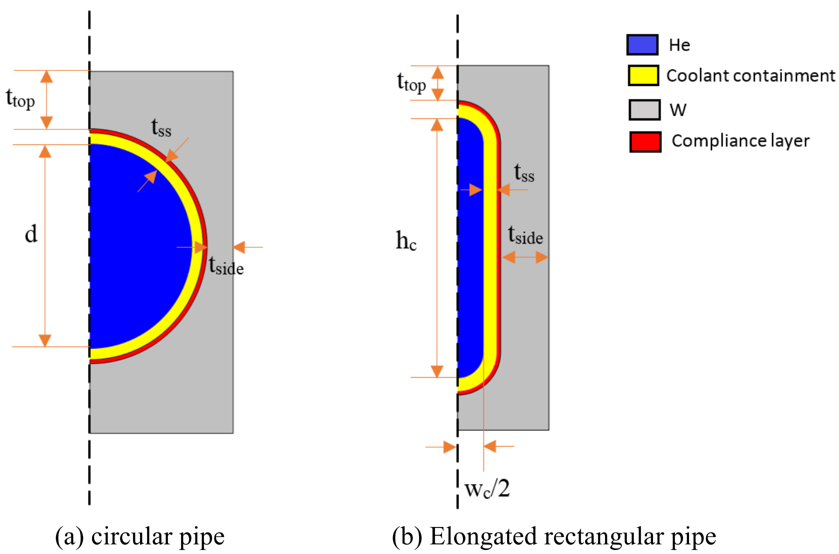


Fig. 2. Concept geometry and adjustable geometric parameters

2.3 Design parameter ranges

Three types of variables play an important role in thermo-mechanical analyses: loading parameters, geometric parameters and coolant thermal hydraulic conditions. For the loading, heat flux was applied on the top surface of monoblock. Nuclear heating was neglected since it accounts for a very small fraction of the total heating (1-2%). No mechanical loadings other than the pressurization of helium coolant were considered. The objective of the design optimization is to maximize the achievable heat flux while satisfying all the material requirements.

To determine the optimal dimensions that could lead to the maximum achievable heat flux, geometric parameter variations have been performed. For the circular pipe configuration, there are four independent parameters that determine the model: W armor thickness (t_{top}), monoblock side thickness (t_{side}), coolant pipe diameter (d) and coolant pipe thickness (t_{ss}). Similarly, the elongated rectangular pipe has five controlling parameters: W armor thickness (t_{top}), monoblock side thickness (t_{side}) and w_c, h_c, t_{ss} for coolant channel width, length and thickness respectively. The compliance layer thickness was set to be constant and not considered in the parameter study since the thickness is small and its variations won't have a significant impact on the results. The parameter ranges for thermo-mechanical analyses are listed in Table 2.

Table 2
Geometric parameter ranges for analyses

Circular pipe		Elongated rectangular pipe	
Parameter	Range (mm)	Parameter	Range (mm)
t_{top}	2 – 10	t_{top}	1 – 6
t_{side}	2 – 6	t_{side}	1 – 6
d	8 – 12	w_c	1 – 5
t_{ss}	0.5 – 2	h_c	10 – 20
		t_{ss}	0.5 – 2

Finally, the assumed helium coolant thermal hydraulic conditions are: 8 MPa inlet pressure, 100 m/s He coolant velocity and inlet temperature equal to the lower temperature limit of the coolant containment material (350˚C for steel or 400˚C for SiC).

3. Analysis

3.1 Analysis and optimization methodology

In order to investigate the maximum heat flux that various advanced monoblock designs can handle, 3D steady state thermo-mechanical analyses have been performed with COMSOL 5.2. For more time-efficient analyses, a symmetry boundary condition was used such that only half of the component was studied. Basically, the simulation includes two parts, which are steady state thermal analysis and thermo-mechanical elastic analysis.

For the thermal analysis part, conservation equation for heat transfer in solids and Fourier's law were applied to the studied domain. Assumed boundary conditions include homogenous heat flux on the top side as well as forced convection and helium pressure on the coolant channel surface. Cooling helium thermal hydraulic conditions, including the inlet temperature and pressure as well as velocity, are discussed in Section 3.2. CFD simulations of coolant were not included in the model. Instead, the heat transfer coefficient was calculated as a function of the wall temperature using the Sieder-Tate correlation for the forced convection regime (with no wall roughening) [17]:

$$Nu = 0.027\, Re^{0.8}\, Pr^{1/3}\, (\mu/\mu_s)^{0.14},$$

where Re is the Reynolds number, Pr is the Prandtl number, μ and μ_s are the fluid viscosity at the bulk fluid temperature and heat transfer boundary surface temperature respectively. This correlation is normally solved by an iterative process, as the viscosity factor will change as the Nusselt number changes. The iteration process starts from calculating the Nusselt number based on the initial wall temperature. Then the heat transfer coefficient is updated, based upon which the new wall temperature can be calculated. The iteration continues until the result converges.

Temperature distribution from thermal analysis together with helium pressure were considered as loads for thermo-mechanical elastic analysis. For the elastic analysis, the following boundary conditions were applied to the model: The fixed boundary condition was applied at the bottom surface of monoblock. Since the coolant pipe and compliance layer are continuous along the axial direction, symmetric boundary conditions were applied to cross-sectioned surfaces of coolant pipe as well as compliance layer. But both ends of W monoblock were set to be free due to castellation. Constant helium pressure (8 MPa) was applied on coolant pipe walls. Temperature and stress (both primary and secondary stress) distributions in different materials were obtained from the thermo-mechanical analyses.

A two-step optimization methodology was used to investigate the optimal design that leads to the maximum allowable heat flux. The first step is to perform a design parameter study so that the influence of each adjustable geometrical parameter on temperature and stress distributions in the monoblock component was understood. Based on the parameter study results, the best combination of different geometrical parameters, which leads to the largest design margin, was roughly determined. In the second step, an optimization module in COMSOL using the Nelder-Mead method was used to determine the optimal design that satisfies all material and design requirements. The optimization module uses the parameters determined in the first step as the initial values so that it searches for the local optimum around the initial values. Besides the initial values of adjustable parameters, three other things need to be determined in order to run the optimization module: objective function, parameter range and constraints. As discussed earlier, the objective of this optimization is to achieve the maximum allowable heat flux. Thus the objective function was set to be the heat flux loading q. Parameter ranges are listed in Section 2.3. Constraints were determined from operating temperature windows and allowable stress intensities of different materials discussed in Section 2.1. Finally, COMSOL provides the optimal results that maximize the objective function without breaking any constraint.

3.2 Results

Following the optimization methodology discussed in Section 3.1, several monoblock designs have been studied, using different materials and coolant containment geometries. Results of the different cases are compared at the end of this section.

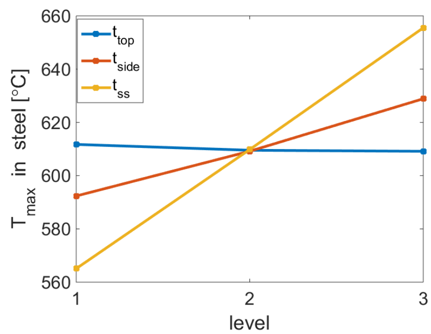
Case 1. Steel pipes

As discussed in Section 2.3, there are four independent geometric parameters controlling the dimensions of the round pipe configuration. However, a parameter study with simultaneous variation of four parameters is too time-consuming. For example, a 3-level 4-parameter full factorial sweep contains 3^4=81 cases. A more efficient strategy is to fix one parameter and sweep all the other parameters. For the round pipe case, the cooling channel diameter d was fixed to be 8 mm so that the overall size is determined and the ratio between any two parameters varies by parametric sweep. A 3-level 3-parameter parametric sweep study was performed in COMSOL based on the values listed in Table 3.

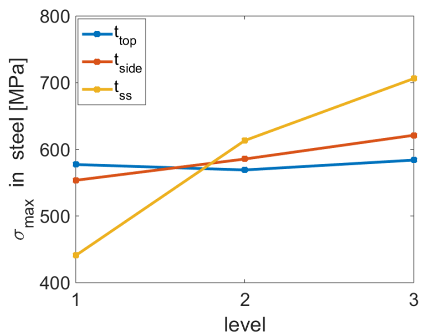
Table 3
Parametric sweep for round pipes

Parameter	Level 1 (mm)	Level 2 (mm)	Level 3 (mm)
t_{top}	2	4	6
t_{side}	2	3	4
t_{ss}	0.5	1	1.5

The maximum temperature and combined stress (primary plus secondary stress) in both steel and W were recorded. It turned out that steel is definitely more constraining than W since both maximum temperature and stress of steel exceed the design limit while W is safe. Thus how different parameters affect the maximum temperature and stress in steel was studied from following plots. The results were based on a heat flux of 2 MW/m^2.



(a) Max temperature in steel

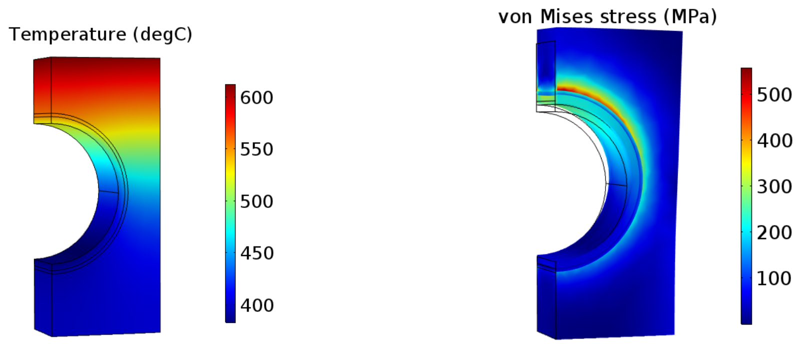


(b) Max stress in steel

Fig. 3. Influence of parameters on the results of steel round pipe analysis

Fig. 3 shows the basic trend of how the maximum temperature and stress in steel change with geometric parameters. One can note that lower t_{side} and t_{ss} (within the studied range) can help increase the design margin while t_{top} has a minor impact on the results. Among the total 27 cases, t_{top}=4 mm, t_{side}=2 mm, and t_{ss}=0.5 mm was the best combination of parameters, and will be used as initial values for optimization in COMSOL.

Once the objective function, parameter ranges and constraints were set, the optimization module in COMSOL was run to search for the optimal solution. Firstly, the case with conventional ferritic steel pipe was studied. It turned out that the optimum solution fitting all design criteria corresponds to t_{top}=3.5 mm, t_{side}=2 mm, d=8.3 mm and t_{ss}=0.5 mm. This geometry can handle a heat flux of **2.1** MW/m^2. Maximum combined stress (P+Q) in steel and W turned out to be 396 MPa and 569 MPa, respectively. Both of them are lower than the allowable stress intensities, 450 MPa and 800 MPa (S_u of W at 613˚C). The maximum combined stress of the steel tube and W exist at the top interface due to the difference of thermal expansion coefficient, as Fig. 4 shows. The minimum temperature in steel is 390 ˚C, while the maximum temperature is 550 ˚C in steel and 613 ˚C in tungsten. The maximum temperature in steel is reached at the top of the cooling tube and at the interface between steel and interlayer. The maximum temperature reaches the material upper temperature limit. Thus, using a material with a higher temperature limit could help accommodate a higher heat flux. Therefore, the ODS steel, which is a more advanced high-temperature steel with a higher temperature limit (650 ˚C) was also studied. The optimum solution is t_{top}=2.8 mm, t_{side}=2 mm, d=8.2 mm, and t_{ss}=0.5 mm and it is able to handle a heat flux of **2.4** MW/m^2. The maximum allowable heat flux was increased only slightly. This is because stress rather than temperature limited the capability of ODS steel. The maximum temperature in ODS steel is only 583 ˚C, which is well below the limit, while the maximum combined stress already reaches the allowable value.



(a) Temperature distribution (b) Total stress distribution in deformed structure

Fig. 4. Thermo-mechanical results of optimum geometry for steel round pipe

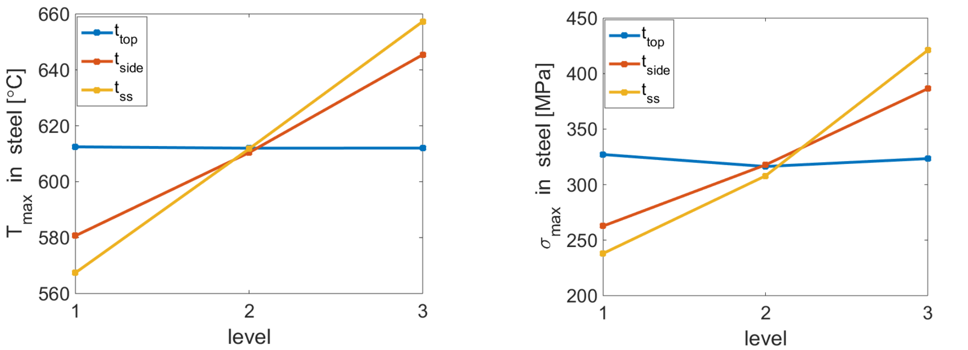
Case 2. Steel microchannels

For a microchannel configuration, there are even more independent geometric parameters than the round pipe case. Based on the same strategy used in Case 1, the parameters determining the cooling channel size (w_c and h_c) were fixed. Only the other three parameters varied, as shown in Table 4. Figure 5 shows the variation of maximum temperature and combined stress in steel as a function of these parameters with a heat flux of 2 MW/m^2.

Similar to the results of Case 1, t_{side} and t_{ss} have a main influence on steel maximum temperature and combined stress, while t_{top} barely affects the thermomechanical results. Thus t_{top}=3.5 mm, t_{side}=2 mm, h_c=10 mm, w_c=1 mm and t_{ss}=0.5 mm were selected as initial values in optimization.

Table 4
Parametric sweep for microchannels

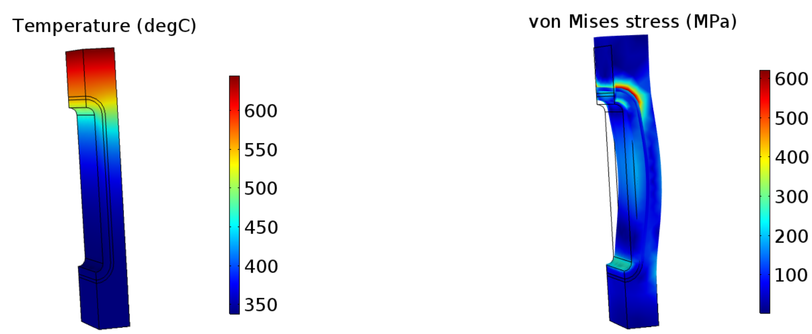
Parameter	Level 1 (mm)	Level 2 (mm)	Level 3 (mm)
t_{top}	2	3.5	5
t_{side}	2	3.5	5
t_{ss}	0.5	1	1.5



(a) Max temperature in steel (b) Max stress in steel

Fig. 5. Influence of parameters on the results of steel microchannel analysis

Again, optimization was performed for both conventional FM steels and ODS steels to show how much we can benefit from extending the upper limit of operating temperature window. It can be seen from the results that FM steels and ODS steels can accommodate a maximum heat flux of **3.7** MW/m^2 and **5.2** MW/m^2, respectively. The optimum dimensions of conventional FM case are t_{top}=3.1 mm, t_{side}=1 mm, h_c=10.3 mm, w_c=1 mm and t_{ss}=0.5 mm. The corresponding results of ODS steel case are t_{top}=3.3 mm, t_{side}=1.1 mm, h_c=10 mm, w_c=1 mm and t_{ss}=0.5 mm. Both FM steels and ODS steels reach the maximum allowable temperature while stresses are still well below the limit, which means even higher achievable heat flux is possible if steels are able to be operated in higher temperature. The FM steel case was taken as an example to show detailed temperature and combined stress distributions in optimum microchannel configuration, as Fig. 6 shows. The peak stress due to thermal expansion difference can be observed at the top interface.



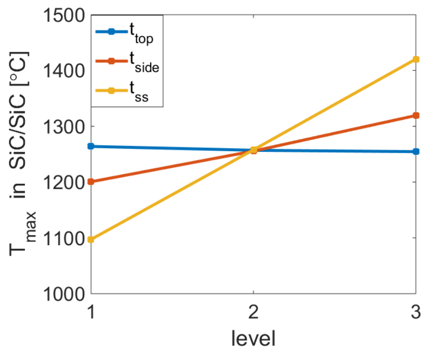
(a) Temperature distribution (b) Total stress distribution in deformed strucuture

Fig. 6. Thermo-mechanical results of optimum geometry for steel microchannel

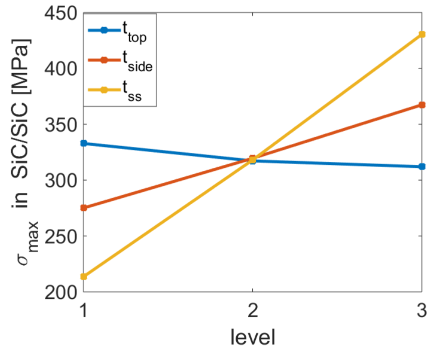
Case 3. SiC/SiC composite round pipe

SiC/SiC composites were studied using a similar analysis process as steels. For a round tube configuration, the parameter sweep study was performed the same as Case 1, as Table 3 shows. The overall size is determined by diameter of tube (d), which was set to be 8 mm in the parameter study.

Again, the influence of geometric parameters on maximum temperature and stress in coolant containment was plotted as Fig. 7 shows. The heat flux was set to be 5 MW/m^2 this time.



(a) Max temperature in SiC/SiC

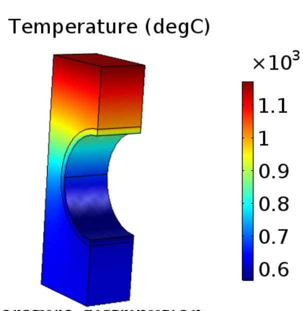


(b) Max stress in SiC/SiC

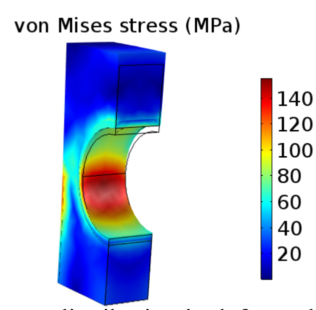
Fig. 7. Influence of parameters on results of SiC/SiC round pipe

Fig. 7 shows that lower values of t_{side} and t_{ss} are more favorable for design. The value of t_{top} doesn't affect the results much. Thus t_{top} =6 mm, t_{side} =2 mm, d=8 mm and t_{ss}=0.5 mm were selected as initial values for the following optimization.

The optimization results showed that the SiC/SiC composite round tube can sustain a heat flux of **4.7** MW/m^2 with the following dimensions: t_{top}=4.7 mm, t_{side}=2 mm, d=8 mm and t_{ss}=0.5 mm. The maximum combined stress in SiC/SiC composite is 157 MPa with maximum primary stress of 18 MPa and secondary stress of 144 MPa, which are both below the corresponding allowable stress intensity. The maximum temperature in the tube and tungsten are 1000 and 1172 ˚C, respectively. Thus the operating temperature window of SiC/SiC is limiting the heat flux. From Fig. 8, it can be seen that the stress at the interface due to thermal expansion coefficient difference was significantly reduced and more continuous compared to the steel cases since SiC/SiC composite has a similar thermal expansion coefficient to tungsten.



(a) Temperature distribution

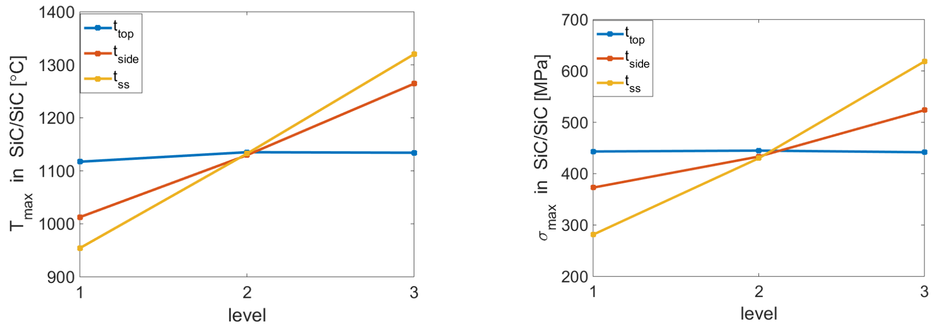


(b) Total stress distribution in deformed structure

Fig. 8. Thermo-mechanical results of optimum geometry for SiC/SiC round pipe

Case 4. SiC/SiC composite microchannels

By replacing the steel in Case 2 with SiC/SiC composite, the fourth case was studied. The parameter sweep study was the same as Case 2, as Table 4 shows. The only difference is that the heat flux was set to be 6 MW/m^2. The corresponding results are shown in Fig. 9.

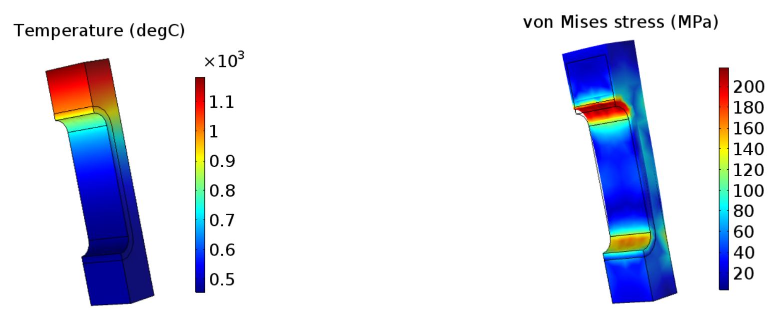


(a) Max temperature in SiC/SiC (b) Max stress in SiC/SiC

Fig. 9. Influence of parameters on results of SiC/SiC microchannels

Similar conclusions as that of previous cases can be obtained from this parameter study. Lower t_{side} and t_{ss} can help achieve larger design margin. Level 1 value of t_{top} is most favorable among three levels considering both temperature and stress results. Initial values for optimization of Case 4 are: t_{top} =2 mm, t_{side} =2 mm, h_c=10 mm, w_c=2 mm and t_{ss}=0.5 mm.

The optimum dimensions of the SiC/SiC composite microchannels are: t_{top} =3.1 mm, t_{side} =1 mm, h_c=10.1 mm, w_c=2.1 mm and t_{ss}=0.5 mm. The maximum allowable heat flux is **7.6** MW/m^2. Results are shown in Figure 10. The maximum temperature in SiC/SiC composite and W are 995 ˚C and 1183 ˚C, respectively. The primary and secondary stresses in SiC/SiC composite are 140 MPa and 98 MPa respectively. The maximum primary stress in SiC/SiC is restricting the maximum allowable heat flux.



(a) Temperature distribution (b) Total stress distribution in deformed structure

Fig. 10. Thermo-mechanical results of optimum geometry for SiC/SiC microchannel

Table 5 and Table 6 summarize the design optimization results of the various cases studied. The numbers in boldface indicate a design limit that restricted the capability of the component to handle a higher heat flux. SiC/SiC composite is shown to be superior to low activation ferritic steel as the coolant containment material in a He-cooled monoblock design since it can achieve higher heat flux. In addition, we found that a microchannel configuration is more suitable than a round pipe when helium is used as the coolant. Effective spreading of heat around the cooling channel is more important due to the lower heat transfer coefficient obtained with He coolant.

Pumping power per unit surface area for each case was also estimated. Pumping power is the product of pressure drop and volumetric flow rate, where pressure drop can be obtained from Bernoulli equation.

Table 5
Summary of thermo-mechanical results for steel cases

Configuration	$T_{pipemax}$ (°C)	T_{Wmax} (°C)	Peak primary + Secondary stress P+Q (MPa)	Allowable temperature (°C)	Allowable stress $3S_m$ (MPa)	Pumping power/area (kW/m^2)	Max allowable heat flux (MW/m^2)
Steel round pipe	**550**	613	396	550	450	32.8	**2.1**
ODS steel round pipe	583	640	**450**	650	450	33.0	**2.4**
Steel microchannel	**550**	645	344	550	450	46.3	**3.7**
ODS steel microchannel	**650**	793	358	650	450	46.6	**5.2**

Table 6
Summary of thermo-mechanical results for SiC/SiC cases

Configuration	$T_{pipemax}$ (°C)	T_{Wmax} (°C)	Peak primary/thermal stress (MPa)	Allowable temperature (°C)	Allowable primary/thermal stress (MPa)	Pumping power/area (kW/m^2)	Max allowable heat flux (MW/m^2)
SiC/SiC round pipe	**1000**	1172	18/144	1000	140/190	29.6	**4.7**
SiC/SiC microchannel	995	1183	**140**/98	1000	140/190	40.6	**7.6**

3.3 Discussion

Besides the configuration, fluid conditions, material properties and design limits also have an impact on the achievable heat flux. For the fluid conditions, higher heat transfer coefficient would help reduce the highest temperature in SiC/SiC while lower pressure will relieve the primary stress problem. For the material properties, higher thermal conductivity of tube material would help enhance the heat transfer. In addition, extending the design limit would help enlarge the design margin and thus improve the performance.

The optimum SiC/SiC microchannel configuration was selected to show how the factors discussed above make a difference. Based on the results in Section 3.2, it can be expected that lower helium pressure may help increase the achievable heat flux since the primary stress in SiC/SiC is the constraint. However, the side effect of reducing the pressure is that the heat transfer coefficient will also be reduced thus leads to a higher maximum temperature in SiC/SiC composite. Since the maximum temperature in SiC/SiC is already 995 ˚C which is pretty close to the limit, there is not much room to decrease the pressure. This means adjusting the pressure is not a suitable method for the SiC/SiC microchannel case. Instead, heat transfer enhancement methods such as roughening the cooling channel surface could help increase the heat transfer coefficient without causing additional stress problems, which will lead to a larger design margin. For the cases where Reynolds number of coolant is around 2.5×10^4, the Nusselt number can be increased to 1.7 times greater by introducing rib-roughened channel walls [18]. With this higher

Nusselt number, simulation results showed that 9.4 MW/m^2 heat flux can be handled (with 8 MPa and 100 m/s coolant).

The effect of thermal conductivity of SiC/SiC composite on achievable heat flux was also studied. The results turned out that the achievable heat flux can be increased to 8.2 MW/m^2 by assuming the thermal conductivity can be increased by 10 W/(mK).

Finally, the impact of stress limits was studied. Assume that allowable primary stress could be increased to 200 MPa, then the achievable heat flux will be able to reach 8.7 MW/m^2. Thermal (secondary) stress limit doesn't affect the results since maximum thermal stress is far below the allowable value as long as the temperature requirement is met.

4. R&D needs

The monoblock configuration was chosen in this study due in part to the large amount of effort already invested in its development. However, we adapted the design in several fundamental ways to a more aggressive longer-term application consistent with the strategy of FNSF and fusion development within the US. Key differences between our approach and that in the existing literature include the consideration of helium as the coolant, slotted as well as round pipe cooling geometries, and advanced materials for cooling channels including NFA steel or SiC/SiC composites.

Tungsten armor enjoys a large international R&D effort as a result of its adoption in ITER and Demo designs. The difficulties and problems connected to the development of tungsten are well known and under investigation. A notable example is the concern over crack growth and its possible impacts on heat transfer to the coolant as well as spalling into the plasma chamber. Analysis and cyclic testing under relevant operating conditions is needed. Since next-step devices are expected to survive much higher neutron damage levels, additional radiation damage data on W armor are needed. The use of tungsten on the first plasma-facing wall may have a negative impact on tritium breeding. We assume that this design would be implemented only sparingly around the plasma, in regions where such high heat fluxes are expected. That combined with the relatively small thickness of tungsten may lead to acceptable results; detailed neutronics analysis will be needed to quantify the impact.

Helium is a top candidate for use in fusion Demo blankets and divertors. It's thermofluid performance characteristics are well established in a variety of flow geometries [19,20]. The monoblock geometry consists of straight channels, for which the heat transfer database is especially well known. Its advantages include chemical inertness, compatibility with other reactor materials, low neutron cross section, and high temperature capability. Helium does not impose any unique limits on operating temperature, allowing us to operate materials within their optimum temperature ranges. The pressure required for adequate heat transfer can be *lower* than that of water, which is constrained by phase change and critical heat flux. Finally, the technology needed for large-scale high-temperature helium-cooled systems already has been developed and implemented in the fission industry [21,22]. For these reasons, we do not believe that the use of helium will lead to significant additional R&D needs. Hermeticity of SiC composites containing high-pressure helium is discussed briefly below with SiC/SiC development needs.

The use of ferritic martensitic (F/M) steel, such as Eurofer or F82H, was considered in large part due to the extensive pre-existing international program of R&D. Material properties are well known and radiation damage studies suggest that the fluence lifetime will be adequate for FNSF provided the material is operated above 350˚C. Even below 350˚C (perhaps down to 300˚C), there is evidence that radiation damage can be annealed with minimal loss of ductility. [7] However, analysis shows that the operating temperature window of ferritic steel prevents the use of the He-cooled monoblock beyond about 3.7 MW/m^2 incident heat flux. For that reason, we also considered advanced versions of steel that offer expanded temperature windows of operation.

Nanostructured ferritic alloys (NFA's) have received increased attention within the fusion community during the past decade. Oxide dispersion strengthened alloys maintain creep strength at temperatures 100˚C or more beyond than conventional alloys, which significanty increases the allowable surface heat flux. These alloys are known to be difficult to manufacture in complex shapes, but the simple pipe geometry of the monoblock is probably within existing technological capabilities. Furthermore, newer castable NFA's (called "CFA's" [23]) may enable common manufacturing techniques while still providing the advantage of higher temperature operation. Irradiation data are more scarce for advanced alloys as compared with conventional F/M steel, but extensive R&D programs are already in place.

Our consideration of non-circular pipes requires an assessment of manufacturability. Extrusion of seamless rectangular tubes is commonly available in sizes above 1 cm; however, the results of our analysis show that smaller channels of the order of 1 mm are needed to achieve the higher performance desired.

Probably the most aggressive assumption in our analysis is the use of SiC/SiC composite pipes. SiC/SiC composites have been explored in international fusion programs for decades [13] and their issues and limitations are known. Issues include hermeticity of SiC composites containing high pressure helium, joining and properties degradation under irradiation. Fortunately, accident tolerant fuel cladding is under serious consideration in the fission industry using SiC composites. R&D on fabrication techniques has led to successful tests with 20 MPa internal He pressure [10]. Recent research on radiation damage indicates that nuclear grade SiC and SiC/SiC composites undergo only minimal swelling and strength changes up to 40 dpa and higher in a fast fission spectrum [24]. The fusion spectrum is expected to produce far more He (and transmutations) than a fast fission spectrum; more data are needed, and the effects of radiation-induced swelling remains to be assessed in the designs under investigation.

Other design-specific issues will require further exploration in order to demonstrate the ultimate performance, reliability and lifetime of this concept. Further research is needed on interlayers between the coolant pipe and armor. Many options exist, and each must be evaluated to establish chemical compatibility, mechanical behavior and radiation lifetime. At present we have not fully designed the manifolding and mechanical attachments to create a complete component design and fully describe design integration issues. Finally, materials development could expand the design window of operation. For example, improvements to SiC composite thermal conductivity could substantially change the optimum design and performance capability.

5. Conclusions

The results of our analysis show that a He-cooled monoblock can provide high performance solutions for both first wall and divertor applications. Heat flux capabilities depend mostly on the temperature window of the material used for the cooling channel and the geometry. A monoblock with ferritic-martensitic steel round pipes is limited to a steady state surface heat flux of 2.1 MW/m^2, increasing to only 2.4 MW/m^2, with the use of advanced steels. The higher allowable temperature of advanced steel can not be fully exploited because in this case the stress limits performance. Some design imrpovements to reduce stress may be productive in pushing the heat flux capability higher.

The use of a slotted "microchannel" geometry provides substantial additional heat flux handling capability. For "ordinary" ferritic steel, the heat flux limit rose to 3.7 MW/m^2, which roughly meets our original goal to double the performance of the previous He-cooled design with W pins. This value rises to 5.2 MW/m^2 using ODS steel. In this case, stresses did not constrain the performance. In either case, the high heat fluxes were obtained in large part by using very small channels: 0.5 mm wall thickness and 1 mm cooling channel width. The thickness of the panel from plasma-facing surface to the back is less than 2 cm. The ability to manufacture these small features and supply the coolant through manifolds needs to be examined.

The use of SiC composite pipes to replace steel and copper was considered in the context of large existing R&D programs developing advanced fission fuel cladding. Fabrication and joining techniques are available, and engineered composite pipes have been shown to withstand up to 20 MPa of internal He pressure. Used inside of a W monoblock configuration, round pipes can satisfy temperature and stress limits up to ~5 MW/m^2 steady state surface heat flux, whereas a microchannel geometry can reach near 8 MW/m^2. This value of heat flux approaches the range expected in a tokamak divertor. Exact specifications of heat flux in the divertor of burning plasma devices are not available, but peak values in the range of 5-15 MW/m^2 are expected.

Our SiC/SiC design variant provides a possible alternative to the He-cooled W-alloy divertor that has been explored in several design studies and R&D programs [25]. The W-alloy divertor has been shown to allow very high performance and heat removal capability, but the availability of an acceptable alloy remains a major uncertainty for its continued development. While SiC composites at present do not achieve the higher heat flux capability of W-alloy, due to limited thermal conductivity, their commercial availability and existing database under neutron irradiation make them a more likely candidate for near-term applications in next-step devices.

Remaining R&D on the SiC monoblock concept have been summarized already in Section 4. The largest uncertainty is probably the influence of 14-MeV neutrons on mechanical properties. Fabrication and design-specific issues are not likely to uncover any fatal flaws for this concept. Based on the attractive features and modest R&D needs, we believe this concept should be further developed and demonstrated.

Finally, there are many parameters involved in the analysis; we were not able to vary all of them in our preliminary evaluation. Some further analysis, for example in optimizing the dimensions that were not varied, may result in performance improvements.

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