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Recent improvements of the helium-cooled W-based divertor for fusion power plants

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ABSTRACT

A number of advanced helium-cooled W-based divertor concepts have been proposed recently for fusion power plant applications within the framework of the ARIES Program. This paper summarizes design optimization and improvements of these concepts based on the minimum and maximum operating temperature of the W structure, pumping power and structural design limits. Re-evaluations of all concepts were performed with increased minimum operating temperature of the W structure from 700 °C to 800 °C in order to avoid embrittlement by neutron radiation. Design adjustments to allow for non-uniform heat flux profiles also have been considered. Comprehensive 3D thermal-fluid and 3D finite element thermo-mechanical analyses have been performed considering both elastic and plastic behavior and results are summarized in this paper.

1. Introduction

The ARIES team has proposed and developed a number of helium-cooled W-based divertor concepts for fusion power plant applications including the larger-scale plate divertor (100 cm poloidal × 20 cm toroidal) [1–3], the mid-size T-tube (1.5 cm in diameter and 10 cm long) [3,4] and the smaller-scale finger concept (∼1.5 cm in diameter for thimble) [2,3,5]. All divertor designs utilize W as sacrificial armor, W or W-alloy as main structural material and advanced ODS (oxide dispersion-strengthened) steel as coolant access tubes and inlet manifold. Both pin-fins and impinging jet cooling schemes have been considered to enhance heat transfer in the high heat flux (HHF) zone [6,7].

In previous studies on helium-cooled W-based divertors for a fusion power plant, a design goal is to accommodate the high heat flux (of the order of 10 MW/m^2) while meeting three main design limits, namely: (a) the minimum operating temperature of the W-structure must be higher than 700 °C in order to avoid embrittlement under neutron irradiation [8]; (b) the maximum operating temperature of the W structure must be maintained below the recrystallization temperature (∼1300 °C); and (c) the required pumping power for the divertor coolant should be less than about ∼10% of the heat extracted from the divertor in order not to have an excessive impact on plant net efficiency. Based on these design limits, the maximum allowable heat flux that remains under 3S$_m$ stress limits of the ASME code were determined to be ∼13 MW/m^2 for the finger design, ∼11 MW/m^2 for the T-tube and ∼9 MW/m^2 for the plate concept, respectively. Recent studies on helium-cooled W-based divertors have shown that the allowable heat flux can be increased by ∼20% if yielding by plastic strain is allowed [5]. However, since fracture toughness of the W alloy is reduced by low temperature irradiation, the lower operating temperature limit must probably be raised to ∼800°C to avoid embrittlement of the W structure material. To achieve this, the helium exit temperature must be raised to a range of 750–800 °**C**. Such a higher helium exit temperature certainly will require a reduction in the maximum allowable heat flux in order to keep the maximum temperature of the W structure under the upper operating temperature limit of 1300 °**C**.

This paper summarizes recent studies on the three helium-cooled divertor concepts, including design modifications, improvements and performance optimizations. Design efforts on adjustments to non-uniform heat flux profile along the plate (poloidal) direction also have been made. "Design by Analysis" rather than "Design by Code" is used to include stress relaxation by plastic deformation, allowing structural materials to exceed the 3S$_m$ limits of the ASME code for pushing to higher heat flux limits.

2. Divertor design improvements

2.1. Plate concept

The original concept of the plate-type divertor proposed by Hermsmeyer and Malang [6] used a pin-fin array for heat

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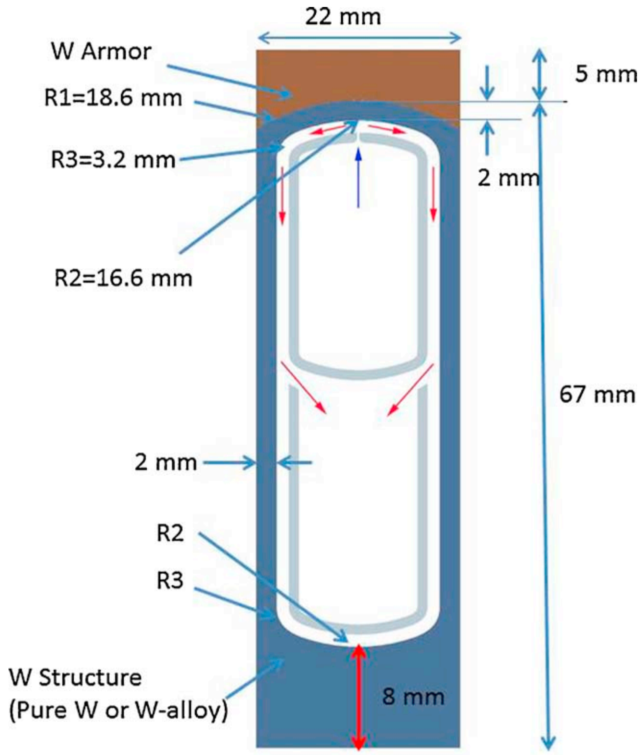

Fig. 1. Schematic of the plate-type divertor.

transfer enhancement and a separate outlet manifold, resulting in an insulating gas gap between the back plate and the outlet manifold. This concept has been proposed to provide a larger scale divertor concept that would minimize the number of units and associated joints containing high coolant pressure. The unit was designed to maintain the temperature distribution as uniform as possible based on the surface heat flux and volumetric heat generation in order to minimize thermal stresses.

In a modified version [1] an additional insulating gas gap together with thicker side and back plates (double thickness of the original plates) are included to minimize the thermal stresses for the given flow conditions and neutron volumetric heating. The plate is made of W or W-alloy with a 5-mm castellated W armor region; it consists of a number of ~1 m long poloidal channels with a 2.2 cm toroidal pitch (a typical toroidal dimension of the plate would be ~20 cm). A thicker back region and a stagnant He insulating gap are used to provide the correct steady-state temperature equilibrium and maintain the primary stress intensity of the W structure in the elastic region ($<S_m$ of the ASME code) and the sum of the primary and secondary stresses under $3S_m$ for heat fluxes up to ~10 MW/m^2.

Modifications and improvements were made by optimizing the slot sizes and cooling conditions to improve the heat transfer with acceptable pumping power, and allowing local yield to account for plasticity in order to push to higher surface heat flux. This led to a modified plate-type divertor configuration as illustrated in Fig. 1 looking more like the original plate-type concept [6].

2.2. T-tube concept

The ARIES T-tube concepts were developed to provide a mid-size unit capable of accommodating at least 10 MW/m^2 for the ARIES-CS power plant [9,10]. The original T-tube divertor is ~15 mm in diameter and ~100 mm long and is made up of W or W-alloy inner cartridge and outer tube on top of which pure W castellated armor layer is attached. Both the W-alloy pieces are connected to a base ODS FS unit through a graded transition to minimize the thermal stresses. The helium coolant is routed through the inner cartridge first and then pushed through thin slots (~0.4 mm) to cool the heat-loaded outer tube surface. The design provides some flexibility in accommodating the divertor area since a variable number of such T-tubes can be connected to a common manifold to form the desired divertor target. Design modifications were made in order to maximize its ability to withstand a higher heat flux while keeping it within all design constraints [4].

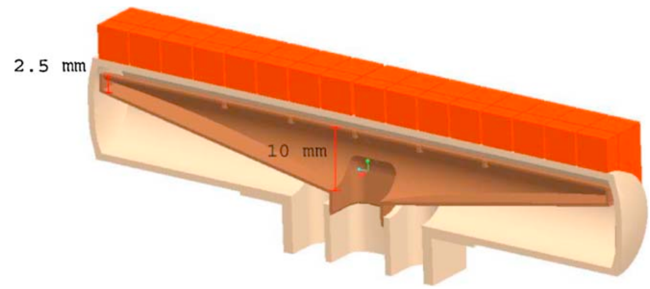

Fig. 2. Schematic of the T-tube divertor.

The modified T-tube divertor design is illustrated in Fig. 2. Recent modifications include:

1. *Inner cartridge modification*. The cartridge will be made from ODS steel (W was selected as the cartridge for the ARIES-CS divertor), which will connect directly to the steel manifold.
2. *Inner cartridge shaping*. The inner cartridge is tapered from an inner diameter 10 mm in the center to 2 mm at the ends. With this modification, a more uniform velocity through the slot-jet, a more uniform temperature distribution along the outer wall and slightly decreased pressure drop are obtained.
3. *Slot-jet modifications*. The size of the slot-jet is decreased and optimized based on temperature, pumping power and stress limits for higher thermal performance and higher heat flux.

2.3. Finger concept

In the EU finger divertor concept [11,12], joining of the W alloy in the thimbles to the ODS steel of the manifold (as necessary in the each of the ~550,000 finger-modules) is very difficult because there is a small temperature window only and the thermal expansion coefficient (TEC) of the W is about 2.5 times smaller than that of ferritic steel. Modifications and improvements to the modular finger design were made to allow brazing the fingers made of VM (Vacuum-Metallized)-W directly into the W plate to avoid connections of dissimilar materials with different TEC [2,5]. The outer diameter of the thimble is enlarged from 18 to 20 mm while keeping the same size of the cartridge. A 1-mm thick cylindrical ring made of VM-W is added inside of the thimble (made of VM-W) covering the mantle of the thimble to provide an additional barrier against high-pressure helium leakage. The W armor, VM-W thimble and VM-W cylindrical ring are brazed together into one armor unit, and then brazed into the W front plate as shown in Fig. 3. In this way, the finger design avoids the transition joints between the W or W-alloy and steel at the modules, and can be considered as providing double containment of the high-pressure helium in the most critical regions.

Further design modifications and optimizations of the layout, sizes and numbers of the cooling jets were performed to improve the heat transfer and push the finger concept to higher performance and higher HFF (high heat flux). Non-linear structural analyses including both material responses of the elasticity and the plastic

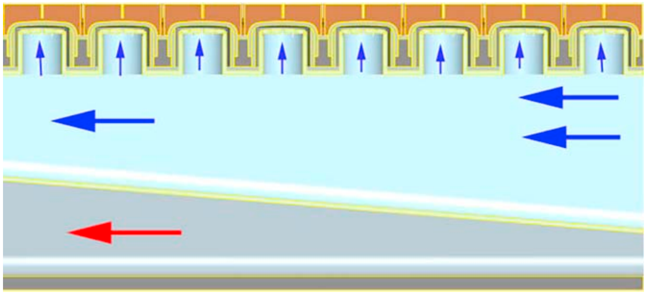

Fig. 3. Schematic of the finger divertor.

deformation (yield) were performed, allowing the materials to be pushed beyond $3S_m$ in order to allow an increase of the maximum heat flux.

3. Analysis

Both elastic and plastic material responses, including stresses, elastic and plastic deformations were calculated for all three concepts. Design and computing iterations were performed using Pro/Engineer, CFX [13] and ANSYS Workbench [14], a state-of-art simulation technology, starting from thermal-fluid analyses to calculate the helium velocity, material temperature (including both the fluid and solid material) and fluid pressure drop distributions, then the nodal temperature and the pressure at the interface of the fluid and the solid being mapped to the ANSYS structural model for the elastic–plastic analyses. These coupled thermo-fluid and thermo-mechanical simulations avoid involving any third computing code and inaccurate data transfer. A standard turbulent flow model k–ε with wall enhancement was used to predict the heat transfer associated with the jet-impingement cooling and the coolant operating pressure of 10 MPa was assumed in all divertor concepts.

The principal design criterion for non-linear structural behavior of the high temperature components is to maintain the maximum plastic strain accumulated over the operating life less than 50% of the uniform elongation [15]. The uniform elongation of W or W-alloy is highly dependent on the material temperature, however very limited data were found from the literature. For pure tungsten, the allowable plastic strain is ~0.8% at a temperature of 270 °C and 1% at ~1200 °C [16]. The temperature-dependent properties for pure W [16] and ODS steel [17] were used in all the CFD and thermo-mechanic analyses.

Fig. 4 illustrates a comparison of thermal performance among the three divertor concepts based on operating temperature (700 °C < T_s < 1300 °C, where T_s is the temperature of the W structure) and pumping power. The pumping power required by the coolant to overcome pressure losses through the divertor loop should be less than ~10% of the removed thermal power. Elastic–plastic analyses indicate in all concepts that stress relaxation by plastic deformation reduces stresses to a degree that the sum of primary and secondary stresses remain below the $3S_m$ limit. The maximum plastic strain in the channel structure and armor for the plate divertor are 0.026% and 0.03% respectively for a maximum heat flux up to ~11 MW/m^2; they are far below allowable plastic strain of 1% for the armor. The maximum plastic strain in the armor of the finger divertor is ~0.13%. In the thimble, the maximum plastic strain is ~0.04% for a heat flux up to 15 MW/m^2. For the T-tube concept, the structure remains within the $3S_m$ limit without yielding for a heat flux up to 13 MW/m^2. These studies demonstrate that temperature and pumping power are the most constraining limits in all concepts.

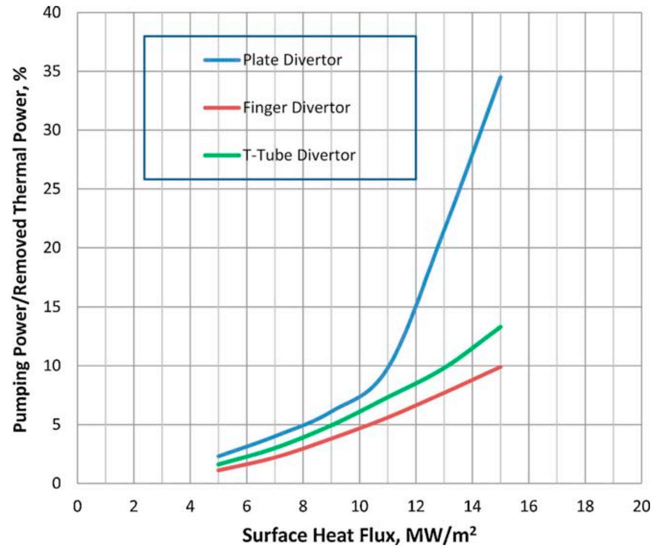

Fig. 4. Comparisons of the thermal performance for all concepts.

3.1. Reduction of the minimum operating temperature

Since the fracture toughness of W or W alloy is reduced by low-temperature irradiation, the lower operating temperature limit of ~700 °C must probably be raised to ~800 °C to avoid embrittlement of the W structure. To achieve this, the helium exit temperature has to be raised to a range of ~750–800 °C (comparing previous cooling conditions of the inlet temperature 600 °C and outlet temperature 700 °C). An advanced ODS steel (such as 12CrYWTi) could be one option for the manifold, functioning as the cartridge for such high cooling temperature. The higher helium exit temperature requires a reduction in the maximum heat flux in order to keep the maximum temperature of the W structure under the upper operating temperature of 1300 °C. New modifications and optimizations have been made to all three divertor concepts with a goal to find the maximum allowable heat flux while obeying the 1300 °C limit for the W structure and 10% limit for the ratio of the pumping to the removed thermal power.

The thermo-fluid results calculated by CFX indicate that the maximum allowable heat flux for the plate concept is ~9 MW/m^2 for a coolant exit temperature of 800 °C, and would be dropped to ~8 MW/m^2 if the maximum allowable operating temperature is assumed to be ~1200 °C, considering that W or W-alloy have lower recrystallization temperature (~1200 °C) as compared with the VM-W (>1300 °C) used as structural material in the finger concept, as illustrated in Fig. 5.

In the simulations and parameter studies, the width of the slot jet for the plate and T-tube concepts and the diameter of the cylindrical jets for finger divertor must be reduced in order to increase the jet velocity and cool the W structure down to the allowable maximum temperature based on the design limits of the pumping power. For the finger concept, the maximum allowable heat flux would be ~14 MW/m^2 if the lower operating temperature of the W structure were raised to 800 °C, roughly ~7% reduction, shown in Fig. 6. The results of the parametric study for the T-tube concept indicate that the maximum allowable heat flux would be reduced from ~13 to ~11 MW/m^2 in order to meet the operating temperature limit (800 < T_s < 1300 °C) and pumping power limit.

3.2. Accommodation of nonuniform heat flux

In previous studies, evaluations were concerned with the layout that achieves the maximum allowable heat flux. There is, however,

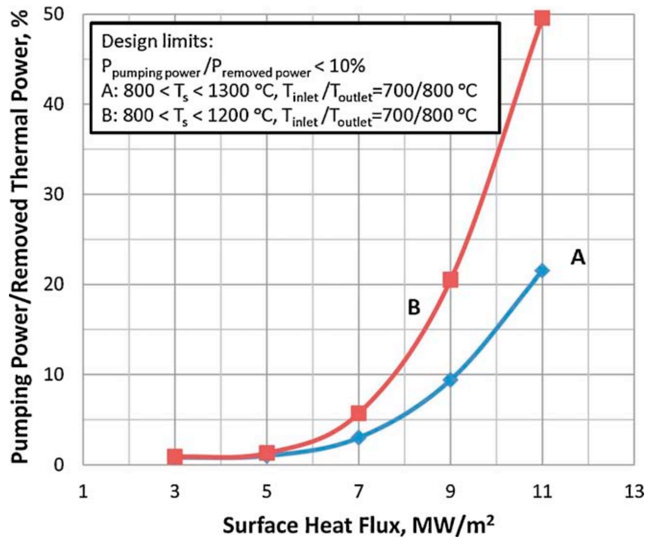

Fig. 5. Parametric studies of the plate divertor showing the allowable heat flux constrained by the operating temperature and the pumping power.

a rather steep profile in the polodal direction with a ratio of maximum to average surface heat flux of ~2–3. Fig. 7 shows an example of a non-uniform heat flux profile for the ARIES-AT fusion power plant [18]. Accommodating such a localized HHF is a challenge for all divertor concepts.

In all divertor concepts, the coolant flows in the poloidal direction in parallel channels. The surface heat flux, cooling condition, and temperatures are equal in these parallel channels. The helium enters at one side of the plate and leaves at the other side. The heat flux into the plate is low at the channel inlet, rises to a maximum value, and drops again in the direction to the exit. Inside the channels there is an inlet manifold with decreasing cross section, and an outlet manifold with increasing cross section. With this arrangement, the helium velocity in both the inlet and outlet manifold remains constant over the entire length of the plate, and the height of the entire channel is constant over the length. Since most of the pressure drop occurs at locations where the coolant leaves the inlet manifold (the nozzles), the coolant pressure remains fairly constant over the length of both manifolds. This means the pressure

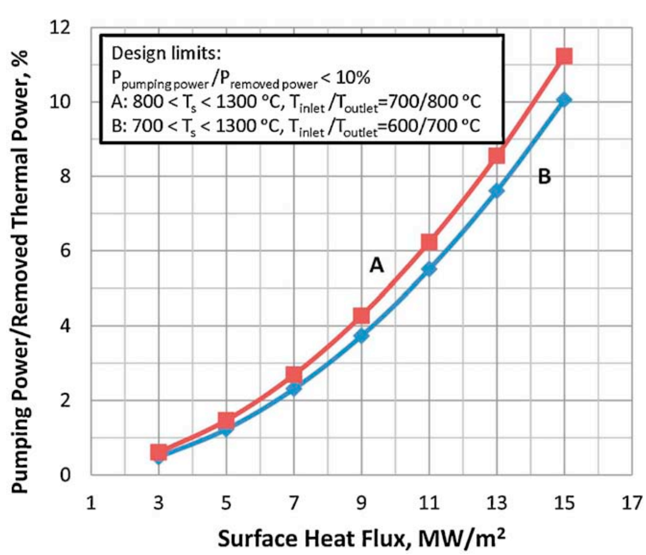

Fig. 6. Parametric studies of the finger divertor showing the allowable surface heat flux constrained by the operating temperature and pumping power.

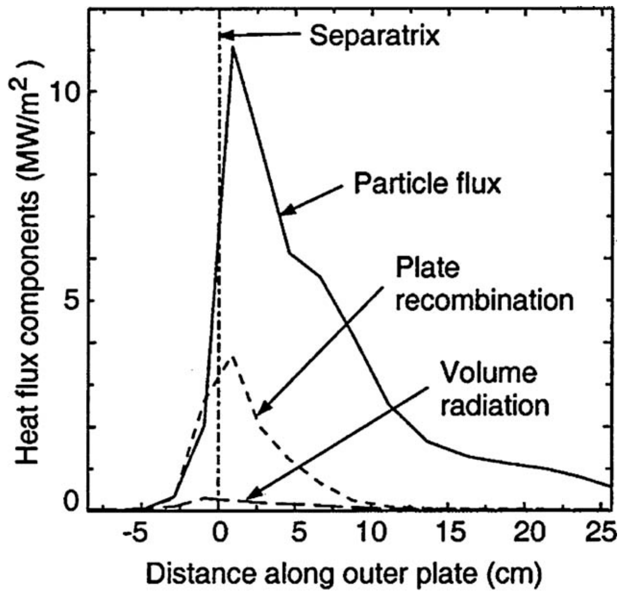

Fig. 7. Heat flux profile for ARIES-AT.

drop in the nozzles generating the cooling jets is constant over the length of the plate. The pressure drop in the nozzle can be estimated by an equation:

$$\Delta P = 0.5\rho v^2$$

Since the pressure drop ΔP and the coolant density ρ remain constant over the length of the plate, the jet velocity v will be constant over the entire plate. It is desirable to avoid mixing of helium with different temperatures. Therefore we suggest keeping the difference between the helium inlet and outlet temperature constant over the length of the channel. To achieve this, the local coolant mass flow rate must be adjusted to the local divertor heat flux, requiring the ratio of the mass flow rate to the surface heat flux to be constant. As the jet velocity is constant over the length of the plate, the flow cross sections (in cm^2 per cm plate length) must be adjusted to the local divertor heat flux, and the ratio of the local cross-sectional area of the nozzles to the cross-sectional area of the nozzles at the location of maximum heat flux must be the same as the ratio of the local heat flux to the maximum heat flux:

$$\frac{S_{\text{nozzle at local}}}{S_{\text{nozzle at max}}} = \frac{q''_{\text{local}}}{q''_{\text{max}}}$$

S_{nozzle} is the cross-section area of the nozzles and q'' is the surface heat flux.

For the plate concept, since the slot should not become too small for practical reasons, the alternative would be to replace a continuous slot by an interrupted slot with a ratio of:

$$\frac{L_{\text{slot at local}}}{L_{\text{slot at max}}} = \frac{q''_{\text{local}}}{q''_{\text{max}}}$$

L_{slot} is the length of the slot.

The same design method would be applied in the finger concept (cylindrical jets). If the nozzle diameter becomes too small for practical reasons, we could keep the nozzle diameter constant and decrease the number of nozzles in the same ratio as the local heat flux decreases.

Detailed 3-D CFD analyses were performed in order to optimize the layout and sizes of jets based on the W operating temperature and the pumping limits. The nonuniform heat flux profile of the ARIES-AT power plant, as illustrated in Fig. 7, was assumed in the analysis. The target plate is about ~30 cm along the poloidal direction, and the helium enters from one side of the plate and leaves from other side. Only the high heat flux region (~50 mm long in the poloidal direction) with maximum heat flux of 11 MW/m^2 was simulated in order to reduce the amount of elements, nodes and computing time. A total of ~4.1 million CFD nodes were generated. The maximum jet velocity is about ~356 m/s, and the corresponding maximum heat transfer coefficient at the interface is ~6.95×10^4 W/m^2-K while the pumping power and the W-structure temperature are under the design limits (<10% and the allowable temperature <1300 °C).

The results of 3D thermo-mechanic modeling indicate that the first principle plastic strain in the W armor and W structure are ~0.03% and 0.032%, respectively, and the plastic design criteria are met. The combined primary and secondary stress at the W thimble is under the $3S_m$ stress limit after stress relaxation by plastic deformation.

It is expected that the finger divertor can handle a localized HHF with higher maximum value (>~15 MW/m^2) than the reference value from ARIES-AT (~11 MW/m^2). Like the plate divertor, the same design adjustment is needed for the T-tube concept to accommodate the localized HHF. This requires the sizes of the T-tube slot jets along the poloidal direction to be reduced in order to maintain the same jet velocity, coolant temperature rise and pressure drop.

4. Summary and conclusions

In this paper, helium-cooled W-based divertor concepts including the plate, T-tube and finger design, have been reevaluated and optimized based on the requirements of raising the minimum operating W structure from 700 to 800 °**C** in order to avoid embrittlement under neutron irradiation. This leads to a decrease in the maximum allowable heat flux from ~15 to 14 MW/m^2 for the finger divertor, and to a ~15% decrease for the T-tube and plate concepts. The maximum allowable heat flux would be further decreased if the maximum allowable temperature of the W-structure were lowered from 1300 °**C** to 1200 °**C**. Such a reduction applies only for the plate and T-tube concepts since W and W-alloy have lower recrystallization temperature than the VM-W alloy used as the structural material in the finger concept.

In our previous studies, all evaluations were concentrated on optimizing the layout of the plate, T-tube and finger concepts and the sizes and numbers of jets for maximum allowable heat flux. Design adjustments to accommodate the power profile in the plate direction must be made by maintaining the jet velocity, coolant temperature rise and pressure drop constant. Results of CFD and thermo-mechanic analyses indicate that the plate divertor concept can handle the ARIES-AT power profile, which has a ratio of maximum (~11 MW/m^2) to average (3.5 MW/m^2) heat flux of 2–3, while maintaining the maximum operating temperature, pumping power and plastic deformation within design limits. The same design method will be applied in the T-tube and finger divertor concepts for handling the localized HHF. It is expected that it will be easier for the finger and T-tube divertor concepts to accommodate the power profile as compared with the plate concept.

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