Transient Thermal and Stress Response of A Helium-Cooled Tungsten Plate-Type Divertor

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Abstract—A number of different helium-cooled divertor design concepts have been proposed for MFE fusion power plant application. The larger-scale helium-cooled Tungsten-alloy plate-type divertor configuration (typically 20 cm (tor.) x 100 cm (pol.) x 6 cm (rad.)) provides an advantage of reduction in number of assembly units in a power plant and the associated reduction in complexity and possibly costs. Transient thermal and thermo-mechanical responses of the divertor plate during the plant startup and shutdown operations have been analyzed with a coupled transient thermo-fluid and thermal-stress approach. Results are presented in this paper.

Keywords-fusion power plant; divertor; thermal-fluid response; thermo-mechanical response

I. INTRODUCTION

Different advanced helium-cooled divertor concepts have been proposed and investigated for power plant applications with a goal of accommodating a heat flux of 10 MW/m². The concepts include: (1) EU FZK smaller scale finger module [1], (2) ARIES mid size T-Tube concept [2], (3) ARIES larger scale plate-type divertor target [3, 4], and (4) ARIES combined larger plate/finger or plate/T-Tube concept [4]. All these design concepts utilize W or W alloy as structural material and employ impinging jet-cooling schemes to enhance heat transfer characteristics. Typically, the smaller dimension concepts like the EU FZK finger and the ARIES T-Tube concept tend to accommodate higher heat flux but at the price of having a larger number of units and associated pressure joints between dissimilar materials, which tend to have a negative impact on reliability. The helium-cooled plate-type divertor design concept proposed within the framework of the ARIES power plant study takes advantage of large modules (20 cm x 100 cm) and reduces the number of divertor units, the fabrication complexity and possibly the cost of the divertor. Three dimensional thermal-fluid and thermo-mechanical results from the supporting analyses indicate that the plate-type divertor concept can accommodate a peak heat flux of 10 MW/m² for a fusion power plant with normal steady-state operation while meeting the temperature, stresses and pumping power constraints [3, 4]. However, concerns exist as to the dynamic stresses in case of the heat flux transient or during the power plant startup and shutdown scenarios for a scheduled maintenance or after the scheduled maintenance because of the different thermal time constants in the front and back parts of the divertor plate.

The transient thermal-fluid response and transient thermo-mechanical response of the plate-type divertor during the plant startup and shutdown operations were performed by a three dimensional CFD code (using CFX [5]) and a three dimensional FE structure code (using ANSYS Workbench [6]). The transient temperature distributions of the divertor plate from the transient thermal-fluid analysis were directly coupled into the thermo-mechanical model as thermal loads to calculate the transient stresses. Results are presented in this paper.

II. PLATE-TYPE DIVERTOR DESIGN

The helium-cooled plate-type divertor design concept has been proposed to take advantage of larger scale units to reduce the number of units, fabrication complexity and possibly cost of the divertor. The goal in designing the plate-type units is to accommodate a high heat flux (of the order of 10 MW/m²) while meeting the main design requirements, namely: (a) the operating temperature of the W plates must be higher than 800 °C in order to avoid embrittlement under neutron irradiation; (b) the maximum structure temperature must be maintained below the re-crystallization temperature of the W alloy (~1300°C); (c) the thermal stresses must be acceptable (Primary + thermal stresses <3Sm); (d) the required pumping power for the divertor coolant should be less than about 10% of the heat extracted from the plates.

Fig. 1 and Fig. 2 show the configuration of the helium-cooled target plate. The plate unit includes (a) a W armor layer with 5 mm (tor.) x 5 mm (pol.) castellation, (b) a W-alloy front plate with grooves for the connection to the side plates, (c) W-alloy side plates, (d) a W-alloy back plate with grooves for brazing in the front plate and the side plates together into one unit, (e) ODS-steel inlet and outlet manifolds, and (f) transition pieces from the W plate to the ODS-steel manifolds at the ends of the plate where the heat flux is low. The front plate with the castellation and grooves is fabricated as a single piece and brazed together with the side and back plates. Each
divertor plate consists of ~8 parallel slot channels with ~1 m poloidal length and 2 cm toroidal pitch, as illustrated in Fig. 1 (a typical toroidal dimension would be 19.2 cm) and Fig. 2. A thicker back plate (4-10 mm), side wall (2-3 mm each side of the filled He at 10 MPa) between the W-alloy side wall and the ODS manifold are employed to raise the average side wall and the back plate temperatures. In this way, the temperature differences between the W front plate (underneath the W armor) and the side/back plates are reduced, and so are the thermal stresses. The thickness of the helium insulator gap and the back plate and side wall thicknesses can be adjusted according to the level of neutron volumetric heating and the surface heat flux on the W armor. An impinging jet cooling scheme similar to the design of the finger [1] and T-tube concepts [2] is utilized to enhance the heat transfer coefficient (in the range of 30–50 kW/m²K) and to cool the front plate effectively, while maintaining an acceptable pressure drop and minimizing thermal stresses.

III. TRANSIENT RESPONSE OF PLANT STARTUP

The results of the thermo-fluid and thermo-mechanical analyses for steady-state operation indicate that the plate-type divertor concept can accommodate a peak heat flux of 10 MW/m² while accommodating the temperature, stress and pumping power constraints under uniform heat load conditions [3]. However, concerns exist as to the dynamic stress in case of heat flux transient or during reactor startup and shutdown because of the different thermal time constants in the front and back parts of the plate.

Plant startup and shutdown operations are required for a fusion power plant for scheduled or un-scheduled maintenance. The plant startup time is dominated by magnet charging, primary coolant system warm up and vacuum system pump-down and it could impose constraints on the plant subsystems, such as first wall, blanket, divertor and power conversion. These constraints are mainly due to the temperature and thermal stress limits of materials utilized in the subsystem. ARIES-I startup and operations [7] were assumed to be the reference startup scenario to calculate the transient thermal and thermo-mechanical responses of the divertor plate. The steady-state conditions were assumed to be attained at ~2500 s. The neutron wall loading and surface heat flux were ramped up at ~2100 s from a very low value (~0) to full power values (with the heat flux $q_s=10$ MW/m² and the neutron volumetric heating $q_v=17.5$ MW/m³) over a 400 s fusion power ramp-up phase. A detailed 3-D transient CFD (using CFX) and 3-D transient thermo-mechanical analyses (using ANSYS Workbench) were performed to explore the allowable heat flux at the divertor plate with respect to the temperature, stress, deflection and pumping power limits.

For the transient thermal-fluid simulation, a constant helium flow rate and constant inlet temperature of 600 °C were assumed. Results from the transient thermal-fluid analysis were directly coupled into the thermo-mechanical model as thermal loads to calculate the transient thermo-mechanical response for the power plant startup operation. The mechanical boundary conditions applied in the analysis include: (1) thermal stresses were assumed to be zero at the coolant inlet temperature (600 °C), (2) the coolant operation pressure is constant (10 MPa), (3) no coolant channel bending is allowed, only free expansion, (4) there are no forces transferred from W armor to the structure [3].

Fig. 3 gives the transient thermal response of the plate divertor for the ARIES-I startup scenario. In particular, the maximum temperature of the W tile, W alloy front structure and W alloy back plate are displayed as a function of operating time. During low fusion power phase ($0 \leq t \leq 2100$ s), the temperature of the plate is close to the coolant inlet temperature (600 °C). At $t=2100$ s, the maximum temperature of the divertor plate starts increasing as the fusion power ramps up and it reaches its peak at full power value (with the heat flux $q_s=10$ MW/m² and the neutron volumetric heating $q_v=17.5$ MW/m³). At $t=2500$ s, the steady-state is attained, and
the maximum temperature of the W armor reaches 1845 °C and the temperature of the W-alloy thimble reaches 1240 °C, which is within the 1300 °C recrystallization limit assumed for W alloy.

![Figure 3. Transient thermal response of the plate-type divertor for ARIES-I startup scenario](image)

**Fig. 3** shows the transient mechanical response of the plate divertor in terms of combined primary (pressure) stress and secondary (thermal) stress at the W-alloy front structure. During low fusion power phase (0 ≤ t ≤ 2100 s), the thermal stress is very small, and the primary (pressure) stress for the helium operating pressure of 10 MPa is about 115 MPa, and the maximum combined primary and secondary stress is 129 MPa. During the fusion power ramp-up (2100 s ≤ t ≤ 2500 s), the maximum combined primary stress and secondary stress of the divertor plate is raised to 325 MPa. This stress level appears to be well within the design limits for the W alloy structure (<3Sm=450 MPa).

![Figure 4. Transient mechanical response of the divertor for ARIES-I startup scenario](image)

**Fig. 4** shows the transient mechanical response of the plate divertor in terms of combined primary (pressure) stress and secondary (thermal) stress at the W-alloy front structure. During low fusion power phase (0 ≤ t ≤ 2100 s), the thermal stress is very small, and the primary (pressure) stress for the helium operating pressure of 10 MPa is about 115 MPa, and the maximum combined primary and secondary stress is 129 MPa. During the fusion power ramp-up (2100 s ≤ t ≤ 2500 s), the maximum combined primary stress and secondary stress of the divertor plate is raised to 325 MPa. This stress level appears to be well within the design limits for the W alloy structure (<3Sm=450 MPa).

**Fig. 5** displays an example of the temperature distributions of the divertor structure (W tile not shown) at the different times during the power ramp-up period. **Fig. 6** shows the distributions of the combine primary and secondary stress at the t=2000 s, 2100 s and 2500 s.

![Figure 5. Temperature distribution of W structure at different times](image)

**Fig. 5** displays an example of the temperature distributions of the divertor structure (W tile not shown) at the different times during the power ramp-up period. **Fig. 6** shows the distributions of the combine primary and secondary stress at the t=2000 s, 2100 s and 2500 s.

**Fig. 6. Combined primary and secondary stress of the W structure at different times**

**IV. TRANSIENT RESPONSE OF PLANT SHUTDOWN**

Operation plans for a power plant includes normal shutdown for scheduled or unscheduled maintenances as well
as emergency shutdown in case of accident situations. There are no details been discussed and described in the past ARIES power plant study or other fusion reactor study regards to the normal shutdown or emergency shutdown scenarios. A reference shutdown scenario was simply assumed to be the reverse of the ARIES-I startup scenario in this analysis. At \( 0 \leq t \leq 400 \) s, the power plant was assumed to be in full power level and the fusion power ramp down was assumed to occur over 400 s.

Like the thermal-fluid analysis of the plant startup scenario, the coolant inlet temperature and the coolant flow rate were assumed to be constant. The mechanical boundary conditions for the structural analysis were assumed to be the same as that of the plant startup scenario. The results of the thermal and mechanical analyses for the shutdown scenario indicate that both the maximum temperature and stress levels in the W structure are within the design limits. The thermal and mechanical responses of the divertor for the shutdown scenario are illustrated in the Fig. 7 and 8.

These results indicate that the divertor plate design can accommodate such gradual ramp-up and ramp-down scenarios within the given stress and temperature constraints. However, faster transients such as in the case of a sudden shift in the heat flux footprint (over 1-10 s) are of concern and should be addressed to better understand the limits of such a concept.

V. CONCLUSIONS

A helium-cooled plate-type divertor design concept has been proposed and investigated within the framework of the ARIES fusion power plant study. Transient thermal and mechanical responses have been performed to explore the allowable heat flux at the divertor plate with respect to the temperature, stress, deflection and pumping power limits under the assumed ARIES-I startup scenario. The results indicate that the transient temperature and stresses appear to be within the design limits of the W and W alloy materials during the fusion power ramp-up to the full power level (10 MW/m\(^2\) of the heat flux and 17.5 MW/m\(^3\) of the neutron volumetric heating) over 400 s (as in the assumed startup scenario) or ramp down for an assumed shutdown over the same time period. However, faster transients (either due to changes in the startup and shutdown scenarios or to a shift in the divertor heat flux profile) need to be considered for a more complete assessment of this concept.

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REFERENCES