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Coupled transient thermo-fluid/thermal-stress analysis approach in a VTBM setting

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ABSTRACT

A virtual test blanket module (VTBM) has been envisioned as a utility to aid in streamlining and optimizing the US ITER TBM design effort by providing an integrated multi-code, multi-physics modeling environment. Within this effort, an integrated simulation approach is being developed for TBM design calculations and performance evaluation. Particularly, integrated thermo-fluid/thermal-stress analysis is important for enabling TBM design and performance calculations. In this paper, procedures involved in transient coupled thermo-fluid/thermal-stress analysis are investigated. The established procedure is applied to study the impact of pulsed operational phenomenon on the thermal-stress response of the TBM first wall. A two-way coupling between the thermal strain and temperature field is also studied, in the context of a change in thermal conductivity of the beryllium pebble bed in a solid breeder blanket TBM due to thermal strain. The temperature field determines the thermal strain in beryllium, which in turn changes the temperature field. Iterative thermo-fluid/thermal strain calculations have been applied to both steady-state and pulsed operation conditions. All calculations have been carried out in three dimensions with representative MCAD models, including all the TBM components in their entirety.

1. Introduction

An integrated simulation and modeling capability able to interface with three-dimensional geometrical models has become an essential tool for practical engineering design of fusion reactor components. Such a capability can significantly reduce the risk and cost involved in laboratory testing as well as in final manufacturing of the component. Ideally, a well conceived virtual fusion engineering computational environment, which integrates geometric models with physical phenomena through proper communication across the various computational modules, reflects the true response of the components for both steady and pulsed reactor operations.

Virtual component engineering simulation provides a tool for fast, streamlined and optimized design efforts through identifying and isolating potential design flaws, while ultimately facilitating simulation of normal and off normal operational scenarios to guide design of the control and data acquisition system. Toward this end, a systematic integrated design approach, through the coupling of computational fluid dynamics (CFD) and structural codes, has been established for steady-state test blanket module (TBM) design performance analysis [1]. The proposed approach has been applied to the first wall cooling manifold design, in which the design must ensure a uniform flow distribution among 16 parallel cooling channels of a TBM first wall, while satisfying temperature and structural stress criteria.

The objective of this paper is to extend this capability to address coupled phenomena, in which the dynamics and/or time-dependent properties of one particular analysis field impact the other field. This can be seen in the case where the effective thermal conductivity of a beryllium (Be) pebble bed depends on both temperature and strain. As plasma burn proceeds, temperature and temperature gradient of a Be pebble bed increase, which then leads to increased stress and strain. The strain generated inside the Be pebble bed can cause a higher conduction through the bed and reduce the temperature and associated gradient. This would lead to a lower stress and a reduced strain. It is possible that, after several pulsed cycles, the Be bed will reach a semi-equilibrium mechanical state, in which temperature in the Be zone no longer varies significantly. However, to accurately account for this coupled behavior in the design analysis is challenging. The challenge lies in accurately mapping the calculated time-dependent strain-induced conductivity from a structural analysis code to a thermal-fluid CFD analysis. In addition, in this paper, the time evolution of a FW panel deformation with respect to ITER H–H phase pulsed operations has been evaluated against stress excursions from temperature his-

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tory in order to reduce design uncertainties. The initial results, as well as the proposed approach to aid into the development of this integrated simulation and modeling for transient analysis, are presented.

2. Analysis methodology and data mapping

The design analysis approach closely follows the well-established procedure of computer aided engineering (CAE) for systematic product design and has been presented previously [1–3]. Specifically, a complete CAD model of the TBM, including the solid and the fluid parts, is input to SC/Tetra (a CFD system) [4], which provides the transient and steady-state temperature field in the solid and fluid parts as well as a three-dimensional coolant flow distribution. The temperature field in the solid components is then imported as loading conditions into the structural analysis system (ANSYS structural code was used for this paper). Typically, a CFD system is based on the finite volume method, while a stress analysis system is based on the finite element method. A method of coupling between CFD system and stress analysis is to convert temperature field data obtained in the CFD stage as input loading data for stress analysis. One advantage of the computational mesh constructed by SC/Tetra is its ability to mesh solid and fluid domains separately. For example, the model can be generated with only tetrahedral elements in the solid thermal-stress domain and with hybrid mesh (a mixture of tetrahedrons, prisms, hexahedrons, etc.) in the fluid domain. Because the hybrid mesh and variables on nodes are compatible between structural analysis FEM elements and node-based CFD elements, not only the temperature distribution of the solid, but also of the mesh, can be directly applied to the thermal-stress analysis. A series of utilities provided along with the SC/Tetra CFD system enable data exchange and mesh interpolation across the CFD mesh onto quadratic tetrahedral elements in the structural analysis mesh. The ability to use separate tailor-made meshes for the thermo-fluid and thermal-stress calculations by the use of data mapping tools between the two is an essential element for integrated multi-physics modeling.

Concern for the accuracy of data mapping has led to the consideration of a higher-order nodal element. The mapping method gives a great advantage if the geometry under analysis is very complicated and if a fine resolution is required in different parts of the geometry in CFD stage and stress analysis stage. For example, when setting up the thermal analysis in the structural analysis code, the analysis can become cumbersome because of the need to define the film heat transfer coefficient as well as the ambient temperature for each individual surface node to arrive at an actual bulk temperature at solid. A method for achieving a higher accuracy is to use higher-order nodes or a much finer mesh size. Previous study [5] has shown when a higher-order tetrahedral node element type of 10 nodes or higher is considered, it could give exact stress/displacement distributions between a CFD/structural data mapping method (where temperature is calculated in CFD code) and a direct method (where temperature is calculated in the structural code with detailed film heat transfer coefficient and ambient temperature). If a finer mesh is used for the first-order element, the difference could also be reduced [6]. In this paper, fine meshes were used.

3. The analysis model

3.1. FW fluid-thermal stress transient behavior

During the initial ITER H–H phase, typical operating conditions for the TBM FW includes an average heat flux of 0.11 MW/m^2 with a pulse length of 100–200 s. The pulse length of 200 s is just about the time needed for the calculated FW structure to reach its thermal equilibrium state. Since not only the temperature, but also the stress, evolves with plasma burns, a weakly coupled CFD and thermal-stress analysis is considered in this paper, in which CFD is solved first and then thermal-stress analysis is solved subsequently. The goal is to evaluate how time-dependent temperature history affects the deformation and stress magnitudes, and whether or not there exists a higher stress during temperature evolution period.

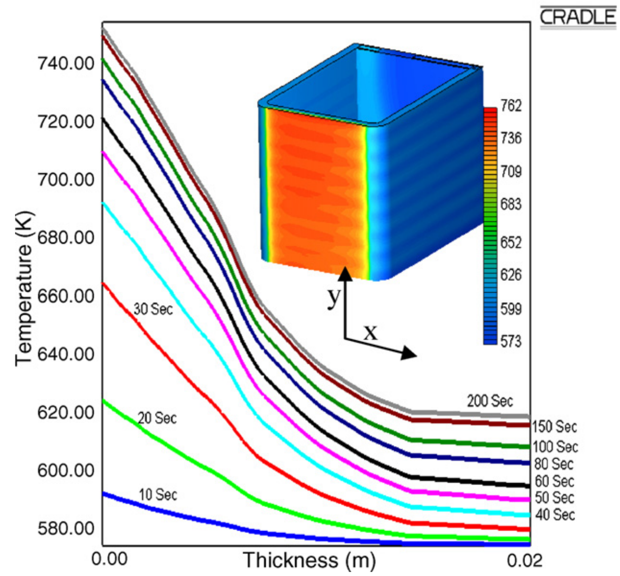

Fig. 1. Typical temperature evolution across the FW thickness (temperatures at the center point shown). Inset: isometric view of temperature profile at the upper FW (x: toroidal, y: poloidal) (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.).

The calculated temperatures across the FW at the center point as a function of operating times are shown in Fig. 1. A key feature concerning temperature evolution along the path is that the temperature near the FW quickly increases to a semi-equilibrium temperature, while the temperature at the back side of the FW increases later. The question is: will the maximum temperature induced by thermal-fluid analysis during the transient process be larger than the maximum temperature difference at the equilibrium point, which may cause a maximum thermal stress not properly accounted for? Since the calculation of the thermal stress and deformation field depends strongly on the applied boundary conditions and initial state of the structure, a lesser constraint is used in order to identify the degree of temperature history effect on stress evolution.

As an example, temperature histories and accompanying stresses across the first wall are shown in Fig. 2. A particularly interesting point is that the stress reaches equilibrium value quicker (~80 s) than does temperature (~200 s), while stress and temperature near the front end of the FW increase asymptotically with respect to time. However, the stress reaches its peak value and falls off to its equilibrium value for locations near the back end of the FW. The stress profile and deformation shape of the plane near the FW cooling channel at different times are shown in Fig. 3. The FW deformed more symmetrically at 60 s, but deformed more toward the location where the fixed degree of freedom constraints are applied during the end of the burn cycle (200 s). The stress increases with time except at some locations near the top and side edges, where it does not vary significantly after 60 s.

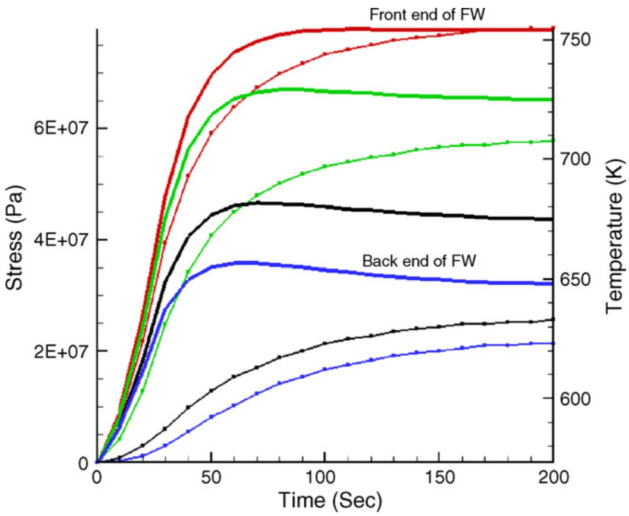

Fig. 2. Temperature and von Mises stress histories at half toroidal plane away from the center plane (at mid-y plane).

3.2. Coupled analysis for fluid–pebble bed thermo-mechanics

The analysis model used to illustrate the integrated thermo-fluid/thermal-stress coupled analysis comprises ~1/5th of the poloidal extent of a proposed HCCB TBM, but includes all the essential elements of the TBM. The temperature distribution in its corresponding CAD model, which includes cooling routes for both first wall and breeding zones, is shown in Fig. 4. It should be noted that the breeding zone temperatures near the sidewalls are much cooler than the bulk temperatures (a reflection of the cooling scheme adopted in the breeding zone). This feature would be cumbersome to obtain if the temperature thermal analysis were

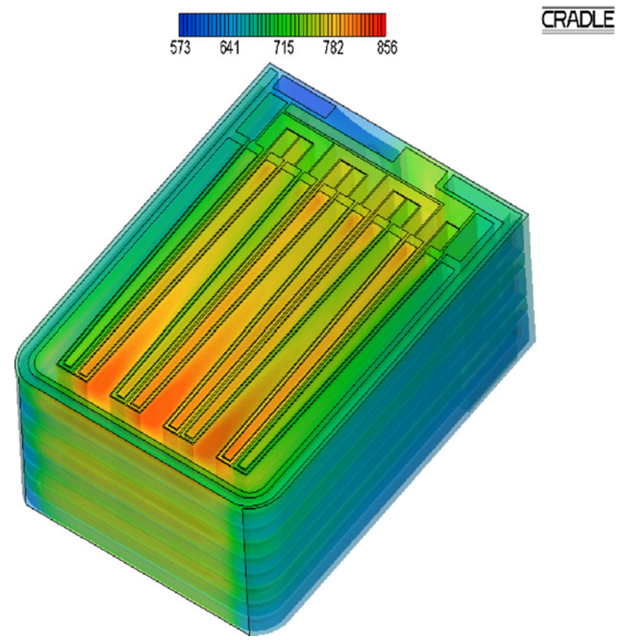

Fig. 4. Isometric view of CAD model with calculated temperature (K) profile (CAD model represents a one-fifth scale of a neutronics TBM). (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

performed in the structural code. The proposed TBM is designed to address neutronics performance of a helium-cooled solid breeder blanket concept and is planned to be tested during ITER's D-T phase. In a typical solid breeder blanket design, the amount of Be in any location is limited by its maximum operating temperature

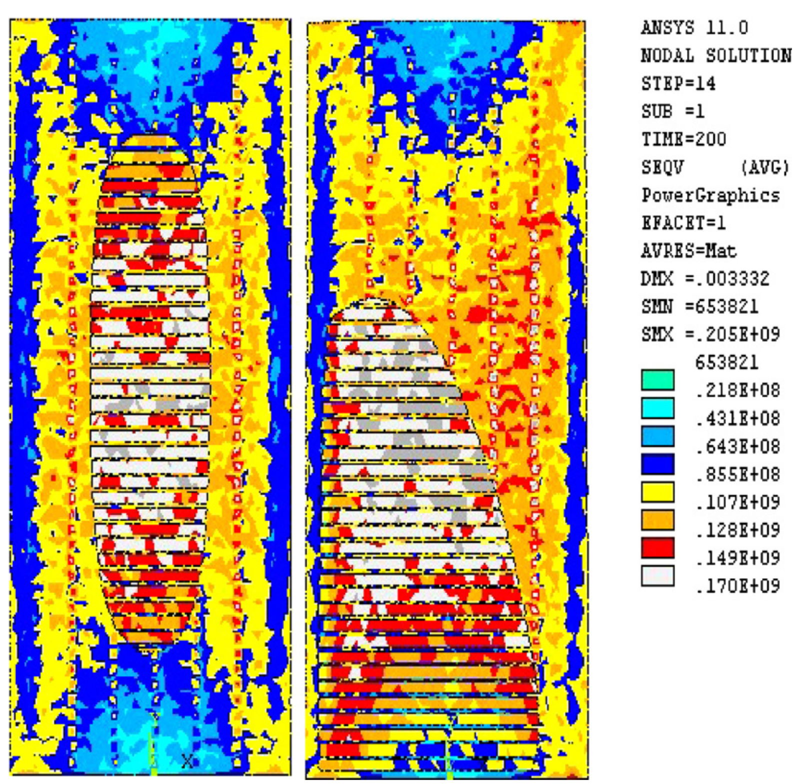

Fig. 3. X (toroidal)–Y (poloidal) plane stress profiles near the front wall of the FW cooling channel (left: 60 s; right:200 s). (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

Table 1
Constitutive equations used in the breeder TBM thermo-fluid and structural analysis

	TBM breeder model
Elastic modulus for Li_4SiO_4 breeder pebble bed [7]	$E = E_0\,(1 - 8.5\,e^{-10} \times T^3)*(1 + 2.458\sigma^{0.83})$, where E: elastic modulus, E_0 = 100 MPa, T: temperature (K), σ: von Mises stress (MPa)
Elastic modulus for Be pebble bed [7]	$E = E'(1 - 8.5\,e^{-10} \times T^3) \times (1 + 2.95\sigma^{0.89})$, where E' = 500 MPa
Strain-dependent effective thermal conductivity for Be pebble bed [8]	$k = C_1(1 - C_2\varepsilon)$, $C_1 = 0.8509 + 4.4576 \times 10^{-3} \times T - 6.532 \times 10^{-6} \times T^2 + 4.014 \times 10^{-9} \times T^3$, $C_2 = 1265.9 - 4.4681 \times T + 7.36 \times 10^{-3} \times T^2 - 4.128 \times 10^{-6} \times T^3$, where k: effective thermal conductivity of Be pebble bed, ε: compressive strain

of ∼600 °C; which may constrain the use of Be to achieve the optimum tritium breeding potential economically. Ideally, it is better to maximize Be concentration near the first wall region, where the kinetic energy of the neutron is beyond the $(n, 2n)$ nuclear reaction threshold energy. Knowledge on the margin of the amount of Be that can be afforded to reduce the maximum operating temperature to about 600 °C through the increase of thermal conductivity due to the effect of the strain can help to optimize the design.

During the D–T phase, where most of the integrated testing will be performed, typical operating conditions for the TBM FW include an average surface heat flux of 0.3 MW/m^2, a neutron wall load of 0.78 MW/m^2, and a pulse length of 400 s with a duty cycle of 22%. Heat transfer processes dominate blanket behavior due to the fact that temperatures impact material properties, thermo-mechanical load, and performance behavior. The transit time for helium flow through the FW and breeding zone is less than 1 s; however, the temperatures in the breeding zone take much longer to reach their equilibrium states under ITER pulsed operations. Thermal stresses can arise due to thermal expansion and temperature gradients and the mechanical constraint of the structure. The stresses will continuously evolve and redistribute during successive heat-up processes, which are strongly influenced by operating temperatures and temperature gradients. The consequence includes breeder/Be particulates rearrangement, strain, and increase in Be thermal conductivity.

To proceed with the analysis, the distribution of the flow field and temperature field was obtained for helium coolant in the first wall, the breeding zone, and the associated collection and distributing manifolds using a CFD code SC/Tetra. In addition, the temperature field was also obtained for the solid domain including the FW ferritic steel structure, breeder and beryllium packed bed zones (Fig. 4). For the purpose of analysis, it was assumed that all the heat was removed by the helium coolant using an adiabatic condition at the outer surface of the TBM structure exposed to the surroundings. Material properties used for the current analysis are listed in Table 1, with other thermo-physical properties consistent with those properties used in a typical helium-cooled solid breeder test blanket design [9].

To develop a working procedure including data transfer of Be thermal conductivity between CFD thermo-fluid and ANSYS structural stress/strain analysis codes and assess the effect of conductivity modification on the CFD temperature results, a steady-state analysis was first performed. This is illustrated by temperature and strain profiles at different iterations shown in Figs. 5–7. An

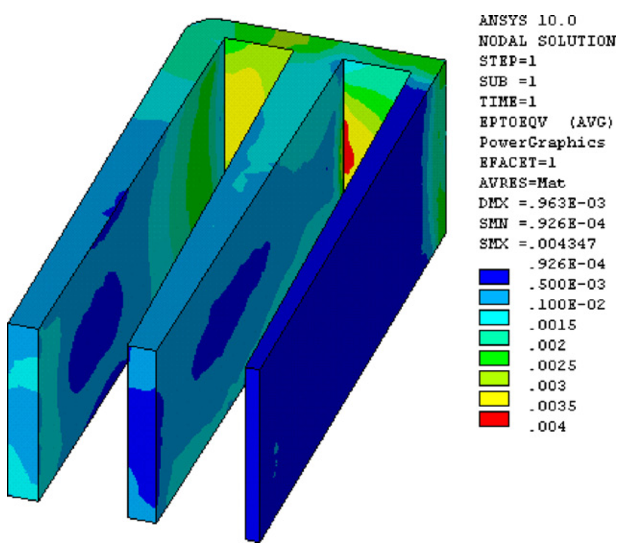

Fig. 5. Isometric view of von Mises elastic strain distribution (half of Be pebble bed computational model shown). (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

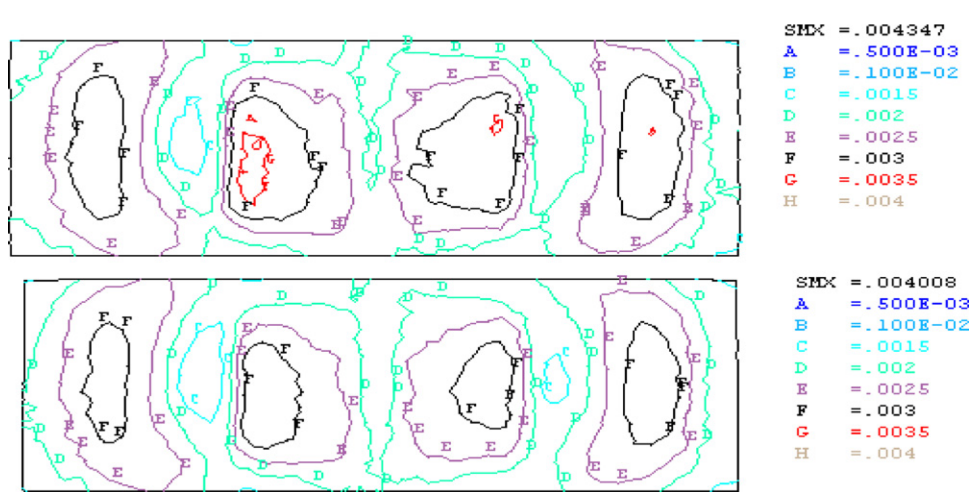

Fig. 6. Be pebble bed strain profiles at 1 cm away from the end of the FW. Top: first iteration; bottom: second iteration. (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

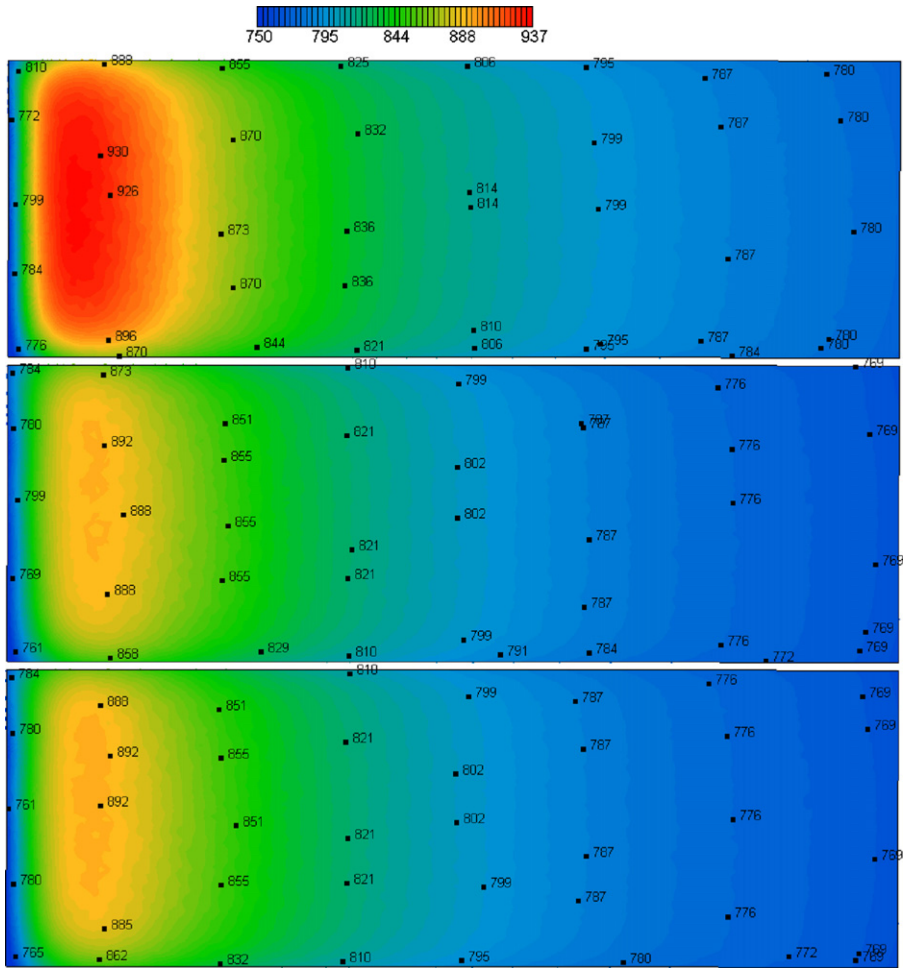

Fig. 7. Be pebble bed mid-plane temperature (K) profiles at different iteration cycles (top: first; middle: second; and bottom: third.). (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

example strain profile inside the Be zone is illustrated in Fig. 5, which shows a quick decrease of strain away from the FW due to an exponential fall-off of nuclear heating profile. The thermo-mechanically induced strain in Be decreases from 0.4347% at the first iteration where Be thermal conductivity values at zero strains were applied to 0.4% when strain corrected Be thermal conductivity values were loaded into the CFD calculations (Fig. 6). In the meantime, the maximum effective thermal conductivity increases from 2.25 to 5.8 W/m^2 K during the first iteration and decreases to 5.4 W/m^2 K at the second iteration. The impacted temperature profiles at different iteration cycles presented in Fig. 7 show the maximum temperature decrease of 43 °C at the first iteration and 1 °C at the second iteration, with a much flatter temperature profile obtained from the third iteration. This amount of temperature difference attributes to an additional 20% of Be added into the front zone region, where neutron multiplication can be enhanced.

The analysis was then performed for an ITER 400-s cycle pulsed operation scenario. To reduce calculation, temperature results at time equal to 200 s were used for stress/strain evaluation, while the resultant thermo-mechanically induced Be thermal conductivity values were applied to CFD code for the remaining 200 s temperature calculations. The Be maximum temperature at 400 s was 19 °C lower (while the colder zone has been widened) when compared with the corresponding temperature without taking into account of strain-induced Be thermal conductivity. It is noted that the temperature near the back manifold region has not yet reached its equilibrium value at the end of the burn.

4. Summary

This paper establishes a working procedure to facilitate coupled three-dimensional thermo-fluid/thermal-stress analysis for the design and performance evaluation of TBM components. An integrated analysis involving a coupled modeling of the coolant flow, temperature and stress/strain fields is required to capture the correct response of the TBM in the prevailing fusion environment. The computational procedures involved in carrying out a flow analysis, a thermal analysis, and a stress and deformation analysis are markedly different. The ability to carry out a successful coupled analysis rests in development of methods that tie together the different physics analyses by providing fast and accurate data mapping, while maintaining the correct sequence of calculation. In this paper, a CFD system (SC/Tetra) has been utilized to obtain the coolant flow and the temperature field in the TBM components. The data from the CFD analysis is mapped onto a structural analysis mesh (ANSYS) to obtain the thermal stress, strain and deformation field. Development of a fast data mapping procedure between the CFD and the stress analysis system has enabled the study of transient thermal-stress response of the TBM first wall to a time varying applied surface heat flux. Interesting findings have been obtained with regards to the time to reach steady-state by the stress field and the temperature field in the first wall structure. A study of two-way coupling between the temperature field and the thermal strain field has also been demonstrated through modeling of strain-dependent thermal conductivity in one of the TBM components. The ability to model strain-dependent thermal conductivity gives a much more accurate prediction of the temperature and stress field ensuing in the TBM components, which can aid in making better informed design decisions. It should be noted that the real emphasis in this paper has been placed on development of the thermo-fluid/thermal-stress coupled calculation procedure. The accuracy of the results and findings from the various analyses will be the subject for later investigation.

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