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Impact of material system thermomechanics and thermofluid performance on He-cooled ceramic breeder blanket designs with SiC_f/SiC

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Abstract

This paper presents results from a recent effort initiated under the JUPITER-II collaborative program for high temperature gas-cooled blanket systems using SiC_f/SiC as a structural material. Current emphasis is to address issues associated with the function of the helium gas considered in the DREAM and ARIES-I concepts by performing thermomechanical and thermofluid analysis. The objective of the analysis is to guide future research focus for a task in the project. It is found that the DREAM concept has the advantage of achieving uniform temperature without threatening blanket pebble bed integrity by differential thermal stress. However, its superiority needs to be further justified by investigating the feasibility and economic issues involved in the tritium extraction technology.

1. Introduction

As a candidate for fusion blanket structural materials, SiC_f/SiC shows significant advantages for use in high temperature operations. Its use has been suggested with LiPb blanket systems as well as with helium-cooled ceramic breeder blanket systems. Thus, both the design and issue relevant R&D emphasis for SiC_f/SiC can be different depending on the breeder/SiC/coolant combination. This paper focuses on the issues derived from a recent effort initiated under the JUPITER II collaborative program and centers around the SiC_f/SiC based helium gas-cooled ceramic breeder blanket systems of DREAM Nishio et al. [1,2] and ARIES-I Najmabadi et al. [3] design concepts. One of the major differences between the DREAM and ARIES-I concepts is the function and the associated operating conditions of the helium gas. This generates an immediate impact on the SiC/breeder/helium material system R&D, and thus warrants a careful evaluation of the merits and feasibility of each concept.

Both design concepts utilize millimeter-size pebble materials for neutron multiplying and tritium breeding regions, with helium gas flowing through it. The helium gas in the DREAM concept serves as the coolant for heat removal as well as the purge gas for tritium removal and flows directly through the pebble bed regions. In contrast, there are two helium streams adopted in the ARIES-I concept: a high pressure, high velocity one which serves as the coolant, and a low pressure stream with a much lower velocity for tritium purge. In this system, only the low-pressure purge gas flows through the packed bed regions. A single gas stream system, as in the DREAM concept, has the advantage of a simpler blanket design with a more uniform temperature distribution to maximize SiC's potential for high thermal efficiency. However, its thermofluid characteristics, such

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as flow distribution and stability, are questionable and become the focus of the present study. On the other hand, the consequence of the thermomechanical interaction between the pebble materials and SiC_f/SiC structural clad poses a threat to the thermomechanical integrity of breeder and beryllium pebble beds. Recent results in this area of JUPITER-II efforts are presented and discussed in Section 3.

2. Thermofluid analysis of helium gas in the DREAM concept

In the DREAM concept, helium gas first flows through the cooling paths in the side wall to the first wall. It then flows into the module through the porous partition wall, cools the internal pebble bed breeding materials and is collected at the outlet pipe. The 10 MPa helium gas enters the module at an inlet temperature of 873 K (in the calculation, the inlet temperature to the blanket zone is set at 938 K). The estimated module flow rate is about 0.48 kg/s for a coolant temperature rise of 250 K in the blanket zone. A typical size of the module is about 0.5 m in the toroidal direction with internal zone sizes of 0.18 and 0.115 m for breeding and multiplier zones, respectively. In addition, a single size pebble bed in the proposed geometrical dimension has a typical packing density of 62% in the bulk region. The analysis of helium gas flow through a packed bed is based on Darcy–Brinkman–Forchheimer's equation for an incompressible steady flow [4]. It states that:

$$\rho\frac{\partial}{\partial x_\beta}(\phi\langle u_\alpha\rangle^i\langle u_\beta\rangle^i) = -\frac{\partial}{\partial x_\alpha}(\phi\langle p\rangle^i) + \mu\frac{\partial^2}{\partial x_\beta^2}(\phi\langle u_\alpha\rangle^i) - \frac{\mu_{\mathrm{eff}}}{K}\phi^2\langle u_\alpha\rangle^i - \frac{F\rho}{\sqrt{K}}\phi^3|\langle u_\beta\rangle^i\cdot\langle u_\beta\rangle^i|\langle u_\alpha\rangle^i, \tag{1}$$

where u_α and u_β are the velocities in the toroidal and radial directions, ρ is gas density, x the coordinate, p the pressure, ϕ the porosity, μ and μ_{eff} are the dynamic and effective dynamic viscosity. The subscript α and β are for coordinates. The superscript i implies that the quantity is defined as the fluid-based average value. Definitions of the permeability (K) and the inertia coefficient (F) can be found in Ref. [4].

A two-fluid, non-thermal equilibrium model is considered to solve the heat transfer characteristics and temperature distribution inside the blanket zone. The energy equations based on Amiri and Vafai [5] are applied to solve the temperature distribution. Additional details in the model include adopting a detailed porosity distribution for the pebble bed Muller [6] and Wakao and Kaguei's [7] model to account for lateral heat dispersion. The numerical model for thermofluid analysis of such a blanket module includes 114×57×40 grid points for a half-blanket region considering symmetry at the center plane. Moreover, the model includes a 3-mm thick membrane partition plate with a 10% porosity to separate the beryllium pebble bed region from the breeder bed region. The SIMPLE method is adopted to solve the aforementioned differential transport equations.

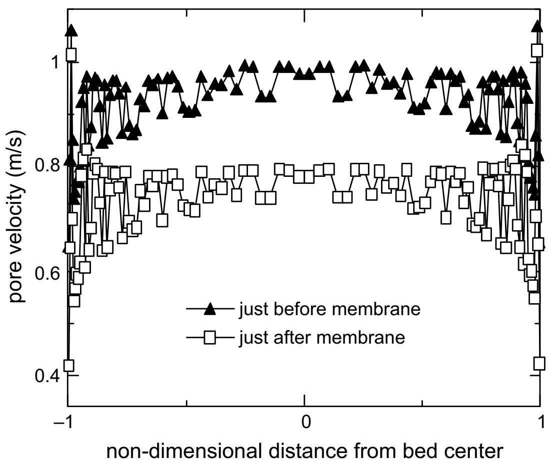

Fig. 1. Spanwise helium velocity profile before and after the partition membrane plate (the total width of the blanket zone is 50 cm).

A distinct feature associated with the velocity distribution is a wall channeling effect, as shown in Fig. 1, where the velocity overshoot can be seen near the sidewalls. This is attributed to the fact that the porosity near the wall is higher and thus the permeability is also higher. The helium flow becomes slightly stagnant behind the partition membrane plate as shown in the same figure. However, this reduction in velocity does not cause a significant increase in the temperature. As shown in Fig. 2, the calculated maximum temperature of 1191 K at the outlet is similar to the estimated temperature according to the simple energy balance analysis of 1188 K. The temperature near the wall is slightly higher than that of the core region because the low conductivity gas is concentrated near the region, as well as the fact that an insulated boundary is assumed. Interestingly, the helium velocity increases as it moves toward the manifold because its temperature magnitude increases. The overall helium pressure drop (~0.2 MPa) is small due to a relatively short flow path.

3. Thermomechanic interaction of breeding pebble beds and SiC/SiC_f structural clad

In the ARIES-I design, pebble beds of lithium ceramics and of beryllium are clad between two SiC composite coolant panels, which are cooled by high-pressure helium gas. A disadvantage of such a design

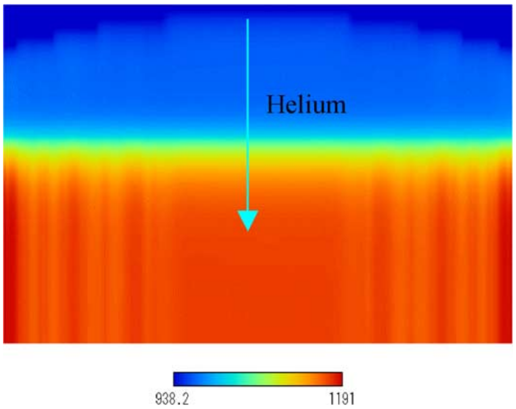

Fig. 2. Helium coolant temperature (°K) profile across the blanket zone.

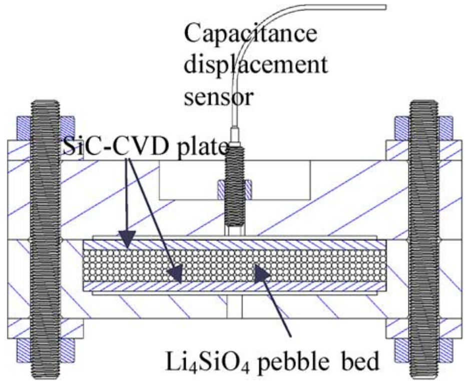

Fig. 3. Schematic view of experimental set-up for thermomechanical interaction study.

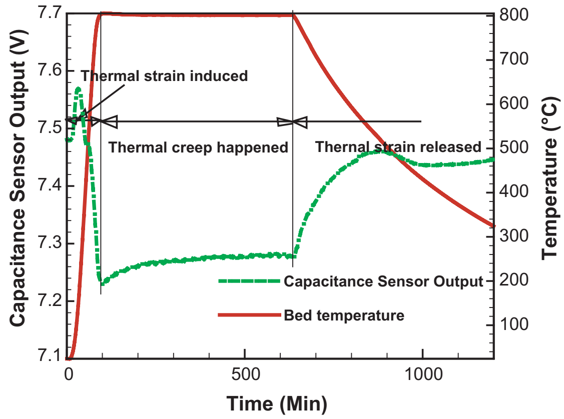

Fig. 4. Deformation traces with respect to temperature history.

arrangement is the narrow operating temperature window for the solid breeder, which undermines the benefit of the high temperature capacity of SiC/SiC_f. A typical operating temperature window for solid breeders such as Li_2TiO_3 falls between 673 and 1193 K. To take full advantage of the SiC operation for high thermal efficiency (such as temperature above 1073 K), this can leave an extremely small temperature window (of ~100 K) for solid breeder operation. The thermal efficiency for ARIES-I is about 46% as compared to the thermal efficiency of 50% as indicated in the DREAM concept. A design goal is to improve the thermal conductance of a relevant SiC/breeder bed unit-cell such that a uniform temperature distribution can be achieved with an engineering practical spacing between SiC/SiC_f coolant panels.

However, a more important issue for such an arrangement is the consequence of the thermomechanic interaction between different blanket elements. During reactor operation, the stresses generated from differential thermal expansion between breeder pebble bed and SiC/SiC_f containment structure, and/or the irradiation swelling of particles may break the particles and endanger safe blanket operation, particularly if heat and tritium removal significantly deteriorate due to ceramic particle breakage. Thus, the determination of the resultant stress magnitude and its evolution is important in the design of a solid breeder blanket. In viewing this, a cylindrical pebble bed thermomechanical test assembly (as shown in Fig. 3) was constructed to evaluate this effect. Specifically, the ceramic lithium orthosilicate pebbles were enclosed between two CVD SiC plates that were fixed at their circumference. In the experiment, the deformations of the top SiC plate, with respect to temperature rise, were measured and shown in Fig. 4. The deformation reflected the amount of bending of the SiC plate under the effect of the differential thermal stress and the applied constrained mechanical boundary. The maximum thermal stress magnitude was estimated to be 2.0 MPa using a bed modulus calculated from a discrete element micro-thermomechanic code Lu [8], which was then inputted to a finite element code MARC [9] for the pebble bed thermomechanical analysis. This small stress magnitude has been significantly magnified at the particle/wall and particle/particle contacts as a result of small contact areas, as shown in Fig. 5. This also caused a thermal creep to occur as revealed in Fig. 4, as the deformation decreased as the bed temperature was kept at a constant value. The effect of temperature on bed thermal creep behavior was studied and presented in Fig. 6. As shown, as creep was initiated, both the stress magnitude and the creep rate were reduced. However, at a bed temperature of 1000 K, the creep evolution followed a parabolic behavior for a longer time, as opposed to the linear function of time observed at lower bed temperatures. The creep as a function of time was studied numerically and compared with the experimental data using a modified effective macro-creep model Bühler [10]:

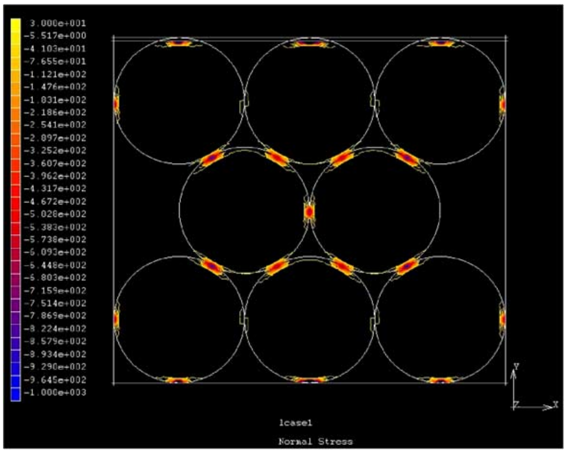

Fig. 5. Calculated contour plot of normal contact stress at particle contacts. The global stress exerted on the plate is 2 MPa, yet the stress at the contact is hundreds of MPas.

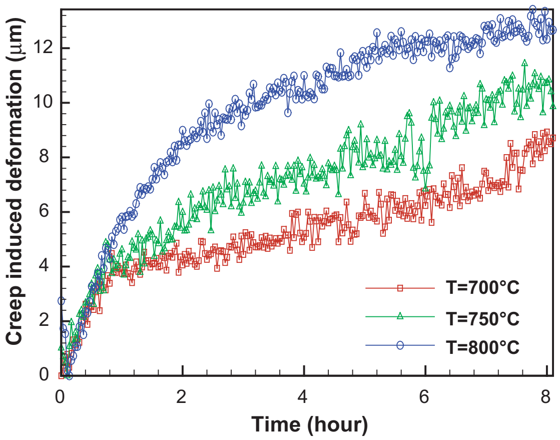

Fig. 6. Effect of temperature on pebble bed system creep evolutions.

$$\dot{\varepsilon} = A(T)\sigma^{1.86}t^{-0.2}, \tag{2}$$

where $A(T)$ has been obtained experimentally Reimann and Wörmer [11], and the macro scale stress σ was estimated through the stress at the contact σ_c using the contact (r_c) and the particle (r_p) radii:

$$\sigma = \sigma_c \frac{r_c^2}{r_p^2}. \tag{3}$$

The comparison shown in Fig. 7 indicated that the numerical simulation by DEM Ying et al. [12] using the Bühler effective macro-model was able to capture the trend of the experimental data concerning thermal creep characteristics; however, the absolute values would still need to be resolved by finding the correct material properties.

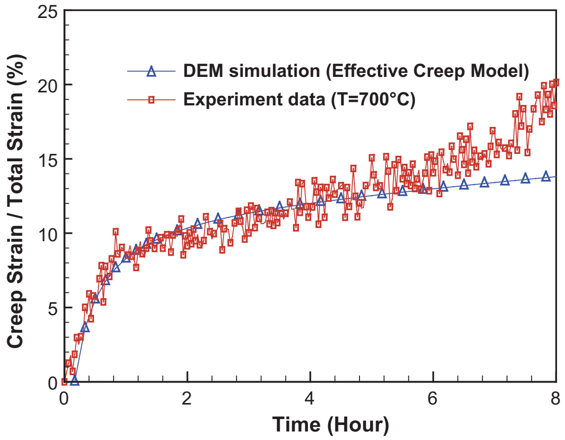

Fig. 7. Numerical versus experimental data on normalized creep deformation as a function of time.

4. Summary

In this paper, two SiC composite structure based helium-cooled ceramic breeder blanket design concepts were assessed and focused on the issues associated with the scheme and function of the helium considered in the designs. The results indicate that flowing helium coolant directly through the pebble beds as in the DREAM concept appears to give a simpler configuration and shows a much more uniform temperature profile in the blanket zone. The wall channeling effect produces a slight disturbance to the helium velocity profile, but does not spoil the temperature distribution. On the other hand, thermomechanical interaction as a result of the operating temperature difference between the breeder pebble bed and SiC/SiC$_f$ coolant plate remains as a key issue for ARIES-I type concept. Design solutions such as spring loading and/or a floating boundary could be implemented to minimize the interaction as well as to accommodate any consequences that result from differential thermal stress and irradiation swelling.

However, the superiority of directly flowing helium coolant through the pebble bed depends on the feasibility and economic considerations involved in tritium extraction. A typical solid breeder blanket design utilizes a low-pressure helium gas for tritium removal. Extracting tritium from the high pressure, high temperature helium coolant could be costly due to a much lower tritium concentration existing in the coolant. This possibility should be assessed.

Acknowledgements

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