EXPERIMENTAL & NUMERICAL STUDY OF CERAMIC BREEDER PEBBLE BED THERMAL DEFORMATION BEHAVIOR

Zhiyong An, Alice Ying, and Mohamed Abdou

Mechanical and Aerospace Engineering Department, UCLA, Los Angeles 90095, an@fusion.ucla.edu

Experiments on thermomechanics interactions between clad and pebble beds have been performed with overstoichiometric lithium orthosilicate pebbles (pebble diameters between 0.25 and 0.63 mm) at temperatures of 700-800ºC. The experimental results show that the thermal deformation of our pebble bed system is nonlinear and when the operating temperature is higher than 600ºC, thermal creep deformation is generated. In this paper, constitutive equations of the elastic and creep deformation are derived from the experimental results. Incorporating the effective constitutive equations in finite element method (FEM), numerical investigations presenting the elastic and plastic deformation characteristics of pebble bed system are comparable to the experimental behaviors. In addition, discrete element method (DEM) is underdevelopment to derive constitutive equations for different pebble beds. The preliminary results of DEM show the stress distribution inside the pebble beds at steady or transient states, which helps us to identify the destructive region in a pebble bed system.

I. INTRODUCTION

In solid breeder blanket design, the ceramic breeder pebble bed system, which is typically operated in a temperature window of 400-900^{o}C, is an important component to fulfill the function of nuclear reactor's blanket. Ceramic pebbles are promising candidates because it can overcome the inherent brittleness of ceramics for use in structural applications, and also have good corrosion and oxidation resistance, high strength and large temperature gradient. However, due to high contact stresses ceramic pebble beds may experience mechanical failure and thermal creep at operating temperature. Thus, a complete description of pebble bed system thermo-mechanics interactions requires analyzing stress re-distributions, damage and failure in the ceramic pebble bed systems under high temperature creep.

The phenomena and parameters involved in ceramic breeder pebble bed thermal deformation are complex. First, unlike solid material, stress distribution in a pebble bed system is highly concentrated at the local zone of contact area. Second, deformation behavior is time-dependent. In order to obtain the knowledge of this bed-structure mechanical interaction, experimental and numerical works [1-3] have been tried to derive the stress-strain relationships and moduli of deformation for the pebble beds. Both research groups in Forschungszentrum Karlsruhe (FZK) and in UCLA have experimentally investigated the behavior of Lithium breeder and beryllium pebble beds and measured the thermo-mechanical behavior of pebble beds. By using finite element method, Fokkons[4] regressed FZK experimental results with the parametric relations, including the loading stress, temperature and deformation. Similarly, Reimann and Wörner[1] provided a correlation, describing thermal creep strain as a function of temperature, pressure and time. Then based on these correlations, the pebble beds can be modeled as a solid material. In addition, it remains to be confirmed that whether the model is applicable to fusion pebble bed operating conditions.

According to previous studies, the initial strain rate of the pebble bed creep deformation can be significant, but as the contact areas in the bed grow, the strain rate can become much relaxed and simultaneously stress magnitude is reduced. Therefore, deformation mechanisms at contact points in the pebble bed system are different and evolve with time. Deformation in the pebble bed may be detrimental and, therefore, understanding its behavior is important to ensure adequate blanket performance.

In this paper, the objective is to study the thermal deformation behavior of the pebble beds. The experimental facility is built and operated under reactor-like temperature operating conditions (700-800℃). The test pebble bed structure represents a simplified model of a typical solid breeder blanket system, which can provide data of fundamental thermal deformation behavior. The recorded data includes the deformation magnitudes of interaction between the structural wall and pebble bed at different times and temperatures. Numerical simulation based on finite element method (FEM) is employed to study details of the deformation. Constitutive equations of the creep model derived experimentally are incorporated into the numerical model. The preliminary results show that the simulation is able to capture thermal deformation characteristics. Furthermore, preliminary study based on discrete element method (DEM) is discussed.

II. EXPERIMENTAL STUDY

The basic elements in solid breeder blanket concepts are the breeder pebble bed and the neutron multiplier pebble bed. In order to separate these beds, structural clad, such as stainless or ferritic steel or SiC-SiC plates, are applied. In the given range of operating temperatures, high thermal stress will occur. The thermal stresses include the stresses between the plates and pebbles and the stresses inside the pebble beds. In general, thermal stresses will not endanger the container structure, but can cause pebbles to rupture near or inside of the blanket structure because of the high contact stresses.

II.A. Experimental Set-Up

To simulate thermal expansion of the beds at high temperatures, our experimental set-up consists of one cylindrical pebble-bed assembly (Fig. 1) and ceramic breeder pebbles packed between two identical SiC plates. The pebble bed model is enclosed by KAVOR (29% Nickerl-17% Cobalt-Steel), which is a vacuum melted, iron-nickel-cobalt, and low thermal expansion alloy. After packing, the height of the pebble bed, along with the thickness of SiC plate at the boundary, is considered as constants during the heat-up process.

For comparability with the experimental model done by FZK, in our design the pebble material is the same pebbles, which are FZK-overstoichiometric lithium orthosilicate pebbles (pebble diameters between 0.25 and 0.63 mm), but the structure has been revised. The details of pebble bed structure and materials properties have been explained in a previous paper.[3]

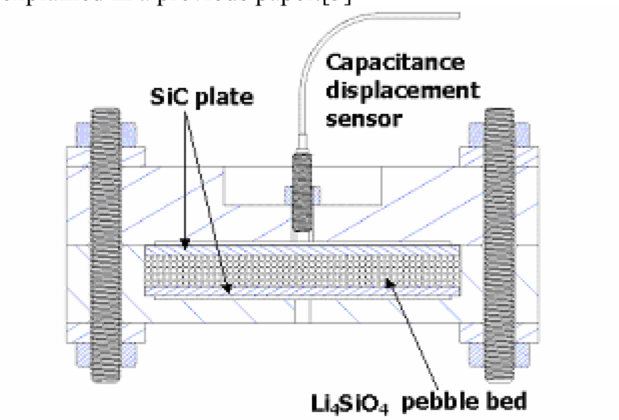

Fig. 1 Experimental set-up for the thermo-mechanics interaction study

In order to describe numerically the pebble bed behavior, fundamental results from a simple experiment are needed. For the experiments, the pebbles were fully filled in a cylindrical container, inner diameter 101 mm (4 inches) and bed height 13 mm. The packing density for each experiment was about 62%. During the experiments, there was no external loading and the cylindrical pebble-bed assembly was heated up to a maximum temperature of 800℃. The tests were performed by pre-heating the beds to 100℃, then, heating up to maximum temperature with 200℃/2hours. After reaching the maximum temperature, the assembly was kept at the same temperature for time periods up to 24 hours. It has been shown[3] as temperature increases and differential thermal expansion of structural and pebble materials generates thermal stress, which accounts for the deformation of the pebble bed. Similar to the FZK experiments, when the temperature is kept at a constant value higher than 600℃, there is time-dependent deformation, which relates to the thermal creep of the ceramic pebbles.

III. Numerical Study

The effective mechanical moduli for the pebble bed appear different from that of the bulk material properties due to the contact behaviors. In the previous studies [4-7], it found that nonlinear elastic and creep compaction behaviors are two major phenomena relating to the stress deformation behavior of the pebble bed. Both of them show the dependence on stress and temperature.

In this section, we show how to regress effective mechanical moduli for the pebble bed based on our experimental results.

III.A. Nonlinear elastic modulus

III.A.1. Fitting Results

To comprise the effective parameters to fit their experimental results, Reimann[4] used the following relation for Young's modulus, which is a function of initial value, Von Mises stress and temperature.

$$E = E_0 \cdot (1 + C_1 \cdot T^{C_2}) \cdot \sigma^{C_3} \qquad (1)$$

where

E : Young's modulus [MPa]

T : Temperature [℃]

E_0: Initial Young's modulus [MPa]

σ : Von Mises stress [MPa]

and C_i are experimentally derived constants.

TABLE I Comparison of parameters for Li_4SiO_4 describing the experimental results [4]

	Reimann fit (temp. increase)	current parameters
E_0	154.0	700.0
C_1	-8.5e-10	-2.5e-10
C_2	3.0	3.0
C_3	0.47	0.3

Incorporating the effective modulus into finite element program, and combining with the experimental results, we found that the fitting parameters for our experiments are different from the 'Reimann fit' parameters. Based on new parameters (listed in table I), the finite element program calculates the bed deformation during heating. The comparison between the experimental results and numerical simulation is shown in Fig.2.

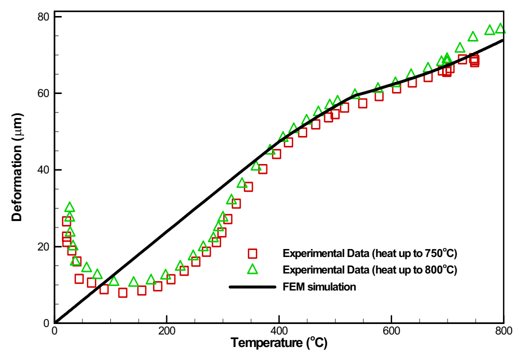

Fig. 2 Comparison between experimental and calculated results

III.A.2. Discussion

Commonly the nonlinear elastic modulus of the packed pebble beds is a function of stress, temperature and material properties. The formula as shown in Eq.1 is a good model to combine all effective parameters together. The model shows that the stiffness of the pebble bed is proportional to the initial compaction stress, and has exponential relationship with the equivalent stress in the pebble beds, but decreases as bed temperature increases.

Using the effective Young's modulus given by Eq.1 in a finite element program, we derived the new fitting parameters, which are listed in Table 1. The fitting curve is plotted in Fig. 2, and the results show that there is more difference at lower temperatures than at higher temperatures. The difference is due to the temperature gradient in the structures when they are heated up at the beginning stage. After a period of time, the temperature distribution in the structure reaches an equilibrium state and then the deformations are more dependent on the material properties.

Comparing current experimental results with Reimann's results, the initial compaction stress are much higher and the temperature and stress dependence are slightly different. These illustrate that the nonlinear elastic modulus of two pebble beds may not be the same even though they are using the same pebble materials. The initial compaction stress is an important parameter to determine the stiffness of different pebble bed systems and depends more on the structure restriction. On the other hand, the stress and temperature effects are related to the material properties.

III.B. Creep model

III.B.1. Fitting Results

Similar to the nonlinear elastic modulus, the creep model is assumed to be a function of stress, temperature and time, and the formula is shown as below:

$$\varepsilon_c = B_0 \cdot \sigma^{B_1} \cdot \exp(B_2 / T) \cdot t^{B_3} \qquad (2)$$

where

ε_c : creep strain
σ : Von Mises Stress [MPa]
T : Temperature [℃]
t : Time [s]

and B_i are experimentally derived constants.

TABLE II Comparison of parameters for Li_4SiO_4 creep model basing on the experimental results [4]

	Reimann fit (temp. increase)	**current parameters**
B_0	11.41	14.605
B_1	0.40	1.5
B_2	-9741.0	-9741.0
B_3	0.20	0.9

Similar to the nonlinear elastic Young's modulus study, the new parameters of creep model are derived using a finite element program. The derived parameters are list in Table II. The comparison of numerical simulation and experimental results are shown in Fig. 3.

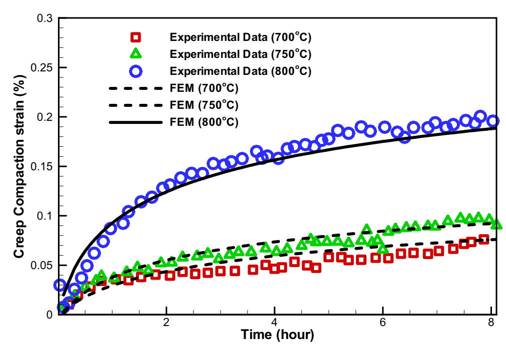

Fig. 3 Comparison between exp. and calculated results

III.B.2. Creep mechanism

When compared to the yield stress of the material, the loading stress on the pebble bed system may not be so significant. However, at the local contact area, the contact stresses can be destructive, and as shown in Fig. 4, the maximum stress in the contact balls is larger than the material's yield stress even though the compaction stress on the balls is only 2 MPa. At high temperature and high stress conditions, the Ashby deformation map[8] is a commonly used method, which represents the regions of temperature and stress in which different creep mechanisms dominate. For instance, in the deformation map, it shows that diffusion creep can be effective at low stresses and at high temperature, and at higher stress the power law creep dominates.

Therefore, when studying the creep model of the pebble beds, the contact stress is important and evolves with time according to constant state. In our creep model (shown in Eq.2), the stress exponent parameter is 1.5 and is higher than that of Reimann's model. It suggests that in our pebble bed system, the stresses have higher effect on the creep strain. This can be related to the higher initial compaction stress, which has been shown in the nonlinear elastic modulus. Since the compaction stress is higher, the contact stresses between the pebbles are also higher, and the creep model will be closer to the power law creep model. Fig. 4 shows the relationship between volume fraction and the stresses of the contact balls under a compaction load of 2 MPa. Since the high stresses volume is relatively small at current experimental conditions, the dominant creep mechanism inside the ball is driven by diffusion creep, in which the stress exponent is about 1.0.

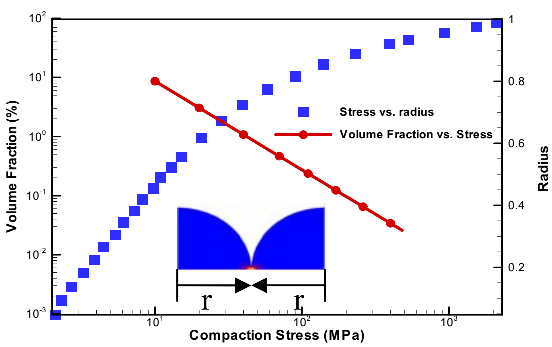

Fig. 4 Stress profile of the contact balls with elastic deformation. The square dot line is stresses vs. radius; the red line with circle shows the relationship between volume fraction and the stresses of the contact balls. (Compaction stress on the balls is 2.0 MPa.)

Furthermore, our model indicates that when pebble materials are applied, the temperature dependent coefficient in the creep model is identical and independent of operating conditions. It means that the temperature effect on the creep model of pebble bed system is only related to the materials.

IV. Discrete Element Method

The differences in nonlinear elastic modulus and creep model between our pebble bed and Reimann's show that the constitutive equations are related to the specific pebble bed design. In this section, the discrete element method is introduced and the preliminary results will show the advantage of this method and its capability to derive constitutive equations of different pebble bed systems.

IV.A Preliminary Results

Constitutive equations of the elastic and creep models derived experimentally can be different when the pebble bed systems are different. In order to effectively derive constitutive equations for different pebble bed systems, discrete element method (DEM) has been considered [9]. For over a decade, discrete element methods have been developed to treat the granular materials as an assemblage of particles interacting through their contacts. This technique was introduced by Cundall [10] to study the motion of rock masses. Since then, DEM has been used to study the statistical micromechanics [11, 12], constitutive behavior of granular sands[5] and soils and plastic/creep behavior of granular materials [6, 7]. The advantage of DEM is its capability to handle particles of any shape and to study the mechanical behavior of those particles based on different loading conditions.

When utilizing the discrete element method to simulate the pebble bed system, each element will stand for one pebble, and it will have the same geometry and material properties of the soil material. After specifying the boundary conditions, all the elements will be rearranged according to the contact force and contact model. The pebble bed structure is updated after the rearrangement and the contact forces at each particle are recalculated. When the numerical simulation achieves the pebble beds equilibrium state, the contact force distribution will follow Ngan's model [13]. Fig. 5 is the result of our simulation. In Fig. 6, a 2-D simulation displays the force distribution inside the pebble beds at the equilibrium state.

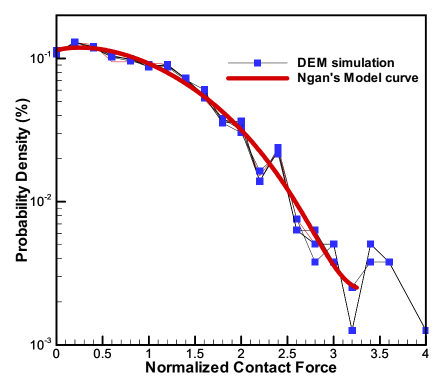

Fig. 5 DEM simulation results of contact force distribution in 2-D (Contact forces are normalized by the mean value)

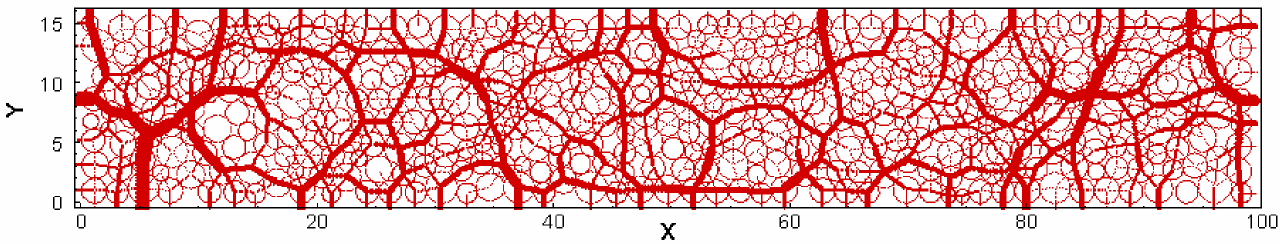

Fig. 6 2-D simulation of force distribution inside the pebble beds (The line stands for the contact force, and its width is proportional to the force magnitude.)

According to the preliminary results, a DEM program can simulate the stress and deformation behavior of a given pebble bed system and the input information for the calculation is the material properties and contact model, which can be obtained easily. The disadvantage of DEM is that it will be limited by the computational capability.

V. CONCLUSIONS

In this paper, the thermal deformation behavior of the pebble beds has been studied. Compared with previous models, it is found that when the pebble bed systems have different characteristics or when the loading behaviors are different, constitutive equations of the elastic and creep models derived experimentally for the systems will be changed. The initial compaction stress should impact the effective Young's modulus of the pebble bed system and detect on the stress exponent considered in the creep model. The temperature effect on the creep model of a pebble bed system is only related to the materials.

The discrete element method (DEM) has been introduced to provide the constitutive equations for the pebble bed systems. The preliminary results show that the simulation is able to capture thermal deformation characteristics and can provide the detail stress distribution inside the pebble beds at both steady and transient states.

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REFERENCES

1. Reimann, J. and G. Worner, *Thermal creep of Li4SiO4 pebble beds.* Fusion Engineering and Design, 2001. **58-59**: p. 647-651.
2. Hermsmeyer, S. and J. Reimann. *Particle flow of ceramic breeder beds in Bi-Axial compression Experiments*. in *Proceedings of the 10th International Workshop on Ceramic Breeder Blanket Interactions*. 2001. Karlsruhe, Germany.
3. An, Z., A. Ying, and M. Abdou. *Numerical and Experimental Investigation of Thermo-Mechanics Interaction in a Ceramic Breeder Pebble Bed System*. in *American Nuclear Society 15th Topical Meeting Technology of Fusion Energy*. 2002. Washington, DC.
4. Fokkens, J.H. *Thermo-Mechanical Behaviour of Pebble Beds by Finite Element Modelling*. in *Proceedings of the 10th International Workshop on Ceramic Breeder Blanket Interactions*. 2001. Karlsruhe, Germany.
5. Bardet, J.P. and J. Proubet, *Numerical simulation of localization in granular materials*. Mechanics computing in 1990's. 1991.
6. Hoque, E. and F. Tatsuoka, *Elasto-plasticity of sand deformation.* Engineering Mechanics, 1995. **8**: p. 547-550.
7. Bardet, J.P., *Numerical simulations of the incremental responses of idealized granular materials.* International Journal of Plasticity, 1994. **10**(8): p. 879-908.
8. Frost, H.J. and M.F. Ashby, *Deformation-mechanism Maps*. 1982: Pergamon press.
9. Abdou, M., A. Ying, and Z. Lu, *Thermal and Mechanical Properties of Ceramic Blanket Particle Bed Materials: Numerical Derivation.* Journal of Nuclear Materials, 1998. **258**.
10. Cundall, P.A. and O.D.L. Strack, *A discrete numerical model for granular assemblies.* Geotechnique, 1979. **29**(1): p. 47-65.
11. Kishino, Y., *Disc model analysis of granular media.* Micromechanics of granular materials, ed. J.T. Jenkins. 1988, Amsterdam: Elsevier. 143-152.
12. Bagi, K., *Statistical analysis of contact force components in random granular assemblies.* Granular matter, 2003. **5**: p. 45-54.
13. Ngan, A.H.W., *On Probalilistic Distribution of Forces in Granular Materials: A Statisticla Mechanics Approach.* Mat. Res. Soc. Symp. Proc., 2003. **759**: p. 29-33.