J. Plasma Fusion Res. SERIES, Vol. 11 (2015)

Experimental Investigation of Thermal Properties of the Li_4SiO_4 Pebble Beds

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(Received: 23 September 2014 / Accepted: 19 January 2015)

The features of solid breeder blanket concept proposed by the China are the tritium breeding ceramic as pebble beds in several submodules. The thermal properties of ceramic pebble beds are important input parameters for the thermo-mechanical design of solid breeder blankets. The objective of this study is to measure the thermal parameters of Li_4SiO_4 pebble beds using the transient plane source method (TPS). The thermal conductivity, thermal diffusivity and specific heat capacity are simultaneously determined from a single measurement process. The thermal parameters of the bed with non-compressed load were measured at temperatures ranging from room temperature to 600℃. The packing fraction was about 63% for the single size pebble beds. Helium at atmospheric pressure was used as a filling gas. The effective conductivity was measured as a function of temperature. The experimental results showed that the effective thermal conductivity increased with the increase of the average bed temperature.

Keywords: Pebble bed; Thermal properties; Test blanket module.

1. Introduction

Lithium ceramics breeding blanket is considered as one of the most promising fusion blankets and worldwide efforts have been devoted to its R&D. The helium-cooled ceramic breeder (HCCB) with the pebble bed concept was selected in Chinese test blanket module (TBM) design [1]. In the HCCB TBM, Lithium orthosilicate (Li_4SiO_4) is considered as the first candidate tritium breeder and beryllium is used as neutron multiplication. The material-form options for the tritium breeders and neutron multiplier are pebble bed. Using pebble beds in breeder blanket has several advantages. First, bed characteristics can be tailored to obtain the required thermal characteristics. Second, the effective thermal conductivity can be controlled by adjusting the bed characteristic. Third, tritium produced in the pebble beds can be easily removed by the purge gas. In the thermal mechanical design of the HCCB TBM with pebble beds, the thermal properties of the pebble beds is one of the most important design parameters which decides the optimum breeder and multiplier arrangement to keep the appropriate temperature ranges of the breeder and multiplier materials. The pebbles are surrounded by flowing helium which carries away the tritium produced in pebbles. However the helium velocity is so small that the effective thermal conductivity of the bed is not affected by the helium flow and the bed behaves like a stagnant bed [2]. The heat produced in the pebbles is carried away by means of cooling tubes containing high pressure helium (≈8MPa) [3].

At present, over the past ten years, several studies have been made on the heat transfer parameters concentrated on uncompressed pebble beds and compressed pebble beds. The measuring methods have been classified as the following three categories [4]: (i) steady state and transient methods, (ii) radial and axial methods, and (iii) absolute and comparative methods. In the steady state method, temperature distribution is generated in the pebble bed to give the observation of the temperature gradient. Ali Abou-Sena et al [5] built an experimental apparatus to measure the effective thermal conductivity of Li_2TiO_3 pebble bed based on the principles of the steady state and the axial heat flow methods. The pebble bed has pebbles of 1.7-2.0 mm diameter and a packing fraction of 61%. The hot wire method is a standard transient experimental technique, used widely to measure the thermal conductivity of pebbles beds. Remiann and Hermsmeyer [6] measured the thermal conductivity of compressed ceramic breeder pebble beds using the pulsed hot wire method combined with a uniaxial compression tests. A distinct increase of the thermal conductivity with bed deformation was found. Enoeda et al [7,8] measured the effective thermal conductivity of the binary pebble beds by hot wire method. The measured value of the effective thermal conductivity of Li_2O 1mm single packing pebble bed is almost not dependent on the bed temperature. Tanigawa et al. [9] measured the effective thermal conductivity of a compressed Li_2TiO_3 pebble beds using the hot wire method at temperatures ranging from 673K to 973K. At all temperatures, increases of effective thermal conductivity due to the compressive deformation were confirmed. M. Dalle Donne et al. [10-12] measured the Li_4SiO_4 pebble beds temperature distribution in axial, and calculated the heat transfer parameters of the bed. The

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published data on thermal properties of Li_4SiO_4 pebble bed are insufficient and more data are still needed.

In the present paper, a new technique (Transient Plane Source method) has been applied to measure the thermal parameters of tritium breeder pebble bed. Then, temperature dependence and thermal properties, including thermal diffusivity, thermal conductivity and specific heat, were investigated.

2. Experimental

2.1 Method

The Transient Plane Source (TPS) method for measuring the thermal conductivity and thermal diffusivity has been used in a variety of situation and for a number of different materials. The experimental principle of the TPS method is based on the transient temperature response of an infinite medium to step heating of a disk-shaped plane source. In the measurement of the TPS method, the sensor serves both as a heater and a temperature detector. The temperature rise in the sensor surface is accurately determined through resistance measurement, and also highly dependent on the thermal transport properties of the test specimen surrounding the sensor.

In this study, the thermal constant analyzer test system (TPS 2500S, Hot Disk, Sweden) has been employed. The Mica sensor (a type of sensor for high temperature measurement) was horizontally embedded in the center of the pebble bed. The radius of the sensor is 9.719 mm and the thickness is 0.1 mm. The temperature range of the electric furnace is from ambient temperature to 600℃. Stagnant helium at atmosphere pressure was used as a filling gas. After reaching the steady state for each experimental run, the sensor is heated by a constant electrical current for a short period of time. The generated heat dissipates from the sensor into the surrounding sample material, which results a rise in temperature of the sensor and surrounding sample material.

2.2 Material

The Li_4SiO_4 pebble with 1.0 mm in diameter used in this study (shown in Fig. 1), and were fabricated by the melt-spraying technique. These pebbles were conditioned by annealing at 1000 ℃ for 2h to obtain the thermodynamically stable phase, lithium orthosilicate and metasilicate. Using the Hg-porosimetry, a density of approximately 94% T.D. (T.D. = 2.40 g/cm^3) and an open porosity of 5.2% were measured; while a closed porosity of 3.2% was measured by He-pycnometry. SEM (Scanning Electron Microscopy) was used to study the surface microstructure of the pebble, see Fig. 2. Li_4SiO_4 pebbles exhibits the known dendritic solidification microstructure due to rapid cooling. The pebbles were packed into a container made of stainless steel and tapped into place by hand. The packed bed was 45mm in diameter and 50mm high, see Fig. 3. The packing ratio, which is the ratio of the total volume of pebbles to the volume of the container, is about 63%.

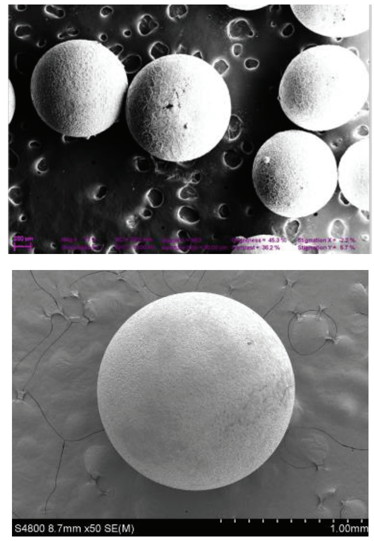

Fig.1 Photograph of Li_4SiO_4 pebble with 1.0mm in diameter.

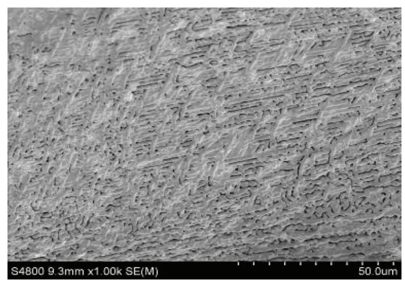

Fig.2 Surface Morphology of pebble.

Fig.3 Test sensor and Pebble container.

3. Results and Discussion

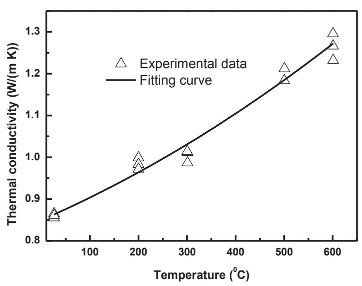

Fig.4 Temperature dependence of thermal conductivity for Li_4SiO_4 pebble beds.

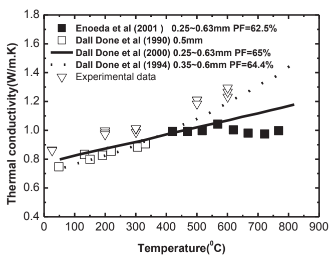

Fig.5 Comparison with previous experimental data.

Figure 4 shows the measured effective thermal conductivity of the Li_4SiO_4 pebbles bed, λ, versus the bed average temperature. From this figure, the effective thermal conductivity of pebble bed increases with the increase of the pebble bed temperature. In other words, the effective thermal conductivity increase from 0.86 W/m K at ambient temperature to 1.29 W/m K at 600℃. The data were correlated in the temperature range of R.T.-600℃ by the following equation:

$\lambda = 0.97198+5.04496\times10^{-4}T+3.30432\times10^{-7}T^2$.

In the heat transfer process, the pebble beds are considered as two-phase (pebbles/gas medium). Thermal conduction through the solid pebbles and thermal conduction through the contact areas are expected to dominate when the filling gas is stagnant and its thermal conductivity is small compared to the pebbles. During initial packing process, all the pebbles are randomly packed into a container and the pebbles are almost point-point contact. With the temperature increase, the pebble beds will generate the thermal deformation. The point-point contact can evolve to face-face contact. The effective thermal conductivity of pebble beds are influenced by many parameters with different extents. Some of these parameters have significant impact on thermal conductivity of the pebble beds, such as thermal conductivity of solid pebbles, filling gas, bed deformation and bed packing fraction. Other parameters have less impact such as pebble size and surface roughness. Thermal conductivity of pebbles and filling gas have direct impact on effective conductivity of the pebble beds. When the ratio of thermal conductivity of pebbles to filling gas is high, the heat flux prefers to follow the path of higher conductivity regions (pebbles and contact areas). Because the helium conductivity is much lower than that of pebbles, the contact area between pebbles directly affects the amount of heat flux across it. It was concluded that the effect of deformation on thermal conductivity cannot be neglected for lithium ceramic pebble beds.

Figure 5 shows the measured effective conductivity of the Li_4SiO_4 pebble beds compared with the previous data. These results indicate the effective thermal conductivity have the same tendency, thermal conductivity increase with the temperature increase. But the measured data are higher than the previous experimental data especially at temperature 500℃ and 600℃. The reason comes from the different measure methods. The contact areas between pebbles with sensor using TPS are larger than hot wire method.

Figure 6 shows the measured the relationship between thermal diffusivity of the Li_4SiO_4 pebble bed α, and the bed average temperature. The thermal diffusivity of the Li_4SiO_4 pebble bed has decreased with the temperature increase. From the results, the thermal diffusivity of pebble beds was about 0.53 mm^2/s at room temperature, falling to about 0.33-0.37 mm^2/s at 600℃. The experimental points are fitted by the following correlation,

$\alpha = 0.54761-4.08679\times10^{-4}T+1.95265\times10^{-7}T^2$.

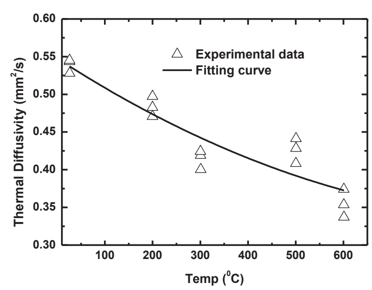

Fig.6 Temperature dependence of thermal diffusivity for Li_4SiO_4 pebble beds.

Fig.7 shows the measured specific heat of the Li_4SiO_4 pebble bed versus the bed average temperature. From the results, the specific heat of Li_4SiO_4 pebble bed increased with the increasing temperature. The empirical equation obtained here is given as following:

$c_p = 1.57753+0.00179T+2.22244\times10^{-6}T^2$.

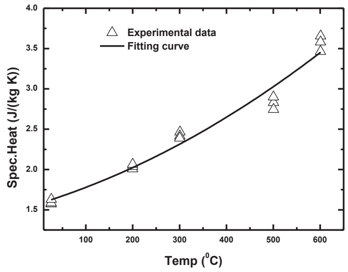

Fig.7 Temperature dependence of specific heat for Li_4SiO_4 pebble beds.

4. Conclusion

The transient plane source method has been applied to measure the thermal properties of single size Li_4SiO_4 pebble beds. The correlations have been developed which describe thermal properties as a function of temperature. It was found that the effective thermal conductivity and effective specific heat increase with the increase of the temperature of the bed. While the thermal diffusivity decreased with the increase of the temperature of the bed.

More experimental studies, with acceptable level of confidence and accuracy, are still required especially for compressed Li_4SiO_4 pebble beds. These experiments will be added to the database of the thermal properties of Li_4SiO_4 pebble beds which can be used for the design and analysis of tritium breeder blankets.

References

[1] K.M. Feng, C.H. Pan, G.S. Zhang et al,. Progress on design and R&D for helium-cooled ceramic breeder TBM in China. Fusion Engineering and Design 87 (2012) 1138-1145.

[2] M. Dalle Donne, A. Goraieb and G. Sordon, Measurements of the effective thermal conductivity of a bed of Li_4SiO_4 pebbles of 0.35-0.6mm diameter and of amixed bed of Li_4SiO_4 and aluminum pebbles, Journal of Nuclear Materials 191-194 (1992) 149-152.

[3] Hu Gang et al, “Updated Design and development route for CH HCCB TBM and its mockup”, Proceedings of the 2013 21st International Conference on Nuclear Engineering ICONE21, July 29- August 2, 2013, Chengdu, China.

[4] E. Tsotsas and H. Martin, “Thermal conductivity of packed beds: A Review”, Chem. Eng. Process., 22 (1987) 19-37.

[5] Ali Abou-Sena, Alice Ying, Mohamed Abdou, Experimental measurement of the effective thermal conductivity of a lithium titnate (Li_2TiO_3) pebbles-packed bed, Journal of Materials Processing Technology 181 (2007) 206-212.

[6] J. Reimann and S. Hermsmeyer, Thermal conductivity of compressed ceramic breeder pebble beds, Fusion Engineering and Design 61-62 (2002) 345-351.

[7] M. Enoeda, et al, Effective thermal conductivity measurements of the binary pebble beds by hot wire method for the breeding blanket, Fusion Technology 34 (1998) 877-881.

[8] M. Enoeda, Y. Ohara, N. Roux, A. Ying, G. Piazza, S. Malang, Effective Thermal Conductivity Measurement of the Candidate Ceramic Breeder Pebble Beds by the Hot Wire Method, Fusion Technology 39 (2001) 612-616

[9] H. Tanigawa, T. Hatano, M. Enoeda, M. Akiba, Effective thermal conductivity of a compressed Li2TiO3 pebble bed, Fusion Engineering and Design 75-79 (2005) 801-805

[10] M. Dalle Donne, G. Sordon, Heat Transfer in Pebble Beds for Fusion Blankets, Fusion Technology 17 (1990) 597-635.

[11] M. Dalle Donne et al. Heat transfer and technological investigations on mixed beds of beryllium and Li_4SiO_4 pebbles”, Journal of Nuclear Materials 212 (1994) 872-876.

[12] M. Dalle Donne, A. Goraieb, G. Piazza, G. Sordon, “Measurements of the effective thermal conductivity of Li_4SiO_4 pebble bed”, Fusion Engineering and Design 49-50 (2000) 513-519.