# EXPERIMENTAL MEASUREMENTS OF THE INTERFACE THERMAL CONDUCTANCE OF A LITHIUM METATITANATE PEBBLE BED

A. Abou-Sena, A. Ying, M. Abdou

*Mechanical and Aerospace Engineering Department, UCLA, Los Angeles, CA 90095*
*aliabousena@engineering.ucla.edu*

*The thermal properties of the lithium ceramics pebble beds have a significant impact on the temperature profile of the Helium Cooled Pebble Bed blanket and the extraction of heat from the pebble beds to the coolant. The literature review showed a lack of experimental data on the interface thermal conductance (h) of lithium metatitanate pebble beds, therefore the objective of this study is to present experimental values of h. The measuring technique is based on the principles of steady state and axial heat flow methods. The lithium metatitanate pebble bed is single size (Ø1.7-2.0mm pebbles) with a packing fraction of 61%. The values of h were measured at the interface of the pebbles with their container's wall (made of stainless steel 316). The results showed that h increased from 1800 to 5300W/m$^2$.K with the increase of the wall temperature from 24 to 570°C. The theoretical values of h, calculated by three models, were compared with the experimental values. The theoretical and experimental values of h showed similar behavior with the increase of temperature. The present values of h will help to create a reliable database of the thermal properties of the lithium ceramics pebble beds.*

## I. INTRODUCTION

The Helium Cooled Pebble Bed (HCPB) blanket is a typical example of the solid breeder blanket concept, where lithium ceramic pebble beds are arranged in layers between cooling plates. These lithium ceramic pebble beds are subjected to volumetric nuclear heating caused by the fusion neutrons; as a result heat is transferred from the hot lithium ceramic pebble beds to the coolant. The thermal properties of the lithium ceramic pebble beds have a significant impact on the temperature profile of the blanket and heat transfer from these pebble beds to the coolant. The effective thermal conductivity $k_{eff}$ and the interface thermal conductance *h*, at the pebbles / cooling plates interface, are the main thermal properties of the lithium ceramic pebbles beds. Predicting the blanket temperature profile is necessary to ensure that the temperatures of each blanket subsystem are within its allowable temperature window. For example the operating temperature of the lithium ceramics pebble beds needs to be maintained within a specific window; where the lower limit is based on acceptable tritium transport characteristics and the upper limit is set to avoid sintering. Any change in the value of *h* affects the temperatures of the lithium ceramic pebble beds because it changes the amount of heat transferred from these pebble beds to the coolant inside the cooling plates. The solid breeder blankets, such as the HCPB, feature shallow lithium ceramic pebble beds which are more sensitive to any change in the value of *h*. A reliable database of *h* and $k_{eff}$ for lithium ceramics pebble beds is needed for the R&D of the solid breeder blanket; therefore the objective of this study is to experimentally measure *h* of a lithium ceramic ($Li_2TiO_3$) pebble bed as a function of the wall temperature from 24 to 570°C.

## II. PREVIOUS STUDIES

In this section, a literature review of the previous experimental studies on *h* is presented. Four previous studies presented data on the interface thermal conductance *h* of lithium orthosilicate and lithium zirconate pebble beds. Two studies[1,2] conducted measurements on *h* of lithium orthosilicate pebble bed. In the first study[1], *h* was measured as a function of bed's temperature (from 51.6 to 333ºC) and a wire mesh was placed at the interface between the pebbles and the wall. This wire mesh caused a significant drop in the values of *h*. In presence of the wire mesh, values of *h* at the outer wall increased from 120.4W/m$^2$.K (at 149.6ºC) to 235.5W/m$^2$.K (at 333ºC), while at the inner wall *h* decreased from 1932W/m$^2$.K (at 149.6ºC) to 861.2W/m$^2$.K (at 333ºC). Without the wire mesh, *h* at the inner wall decreased from 5262W/m$^2$.K (at 51.6ºC) to 4249W/m$^2$.K (at 131.6ºC) and at the outer wall, *h* decreased from 501.1W/m$^2$.K (at 51.6ºC) to 382.3W/m$^2$.K (at 131.6ºC). In the second study[2], *h* of a lithium orthosilicate pebble bed was measured and the authors reported a value of 6000W/m$^2$.K as a design value of $h$. In the third study[3], $h$ of a lithium zirconate pebble bed was measured versus external applied pressures and at different gas pressures (with helium and air). All measurements were conducted at 70ºC and the values of $h$ ranged from 50 to 181W/m$^2$.K with different pressures. The fourth study[4] was presented in 1996 to measure $h$ of a lithium zirconate pebble bed. The authors reported that the values of $h$ scattered between 2000 and 4000W/m$^2$.K with the heater's temperature in the range of 480 to 550ºC. Therefore, no data is available on $h$ of lithium metatitanate pebble beds.

## III. EXPERIMENTAL APPARATUS

The experimental apparatus of this study was designed and built, at the UCLA Fusion Science and Technology Center, to conduct the measurements of $h$. Its design is based on the principles of the steady state and axial heat flow techniques. The main concept of the measuring technique is to generate a temperature gradient across the pebble bed by placing it between a heater and a heat sink. Measurements of the heat flux and temperatures across the pebble bed, after reaching the steady state conditions, are used to calculate $h$. The experimental apparatus consists of the following main parts: pebbles container, heater, heat flux smoother, heat sink, thermocouples, heat flux sensors, heat flux meter, helium chamber, and vacuum chamber. The pebbles and their container form what is called the pebble bed. The pebbles container is a hollow cylinder with inner diameter of 89mm, outer diameter of 101.6mm and height of 50mm. ZIRCAL[5] was used as a pebbles container because it has high working temperature limit (1000°C) and low thermal conductivity (~0.29W/m.K). This low-conductivity container helps to keep the heat flux through the container's walls close to that through the pebble bed. An electric-resistance heater was used to heat the pebbles bed to the required high temperatures. A heat flux smoother (disc of Graphite POCO) is placed between the heater and the pebble bed to uniformly transfer the heat from the heater to the pebble bed.

The temperature gradient of the pebble bed is measured by five two-point thermocouples, see Figure 1. These thermocouples are placed perpendicular to the heat flow in order to minimize their disturbance to the bed's isotherms. The specifications of these thermocouples are given in Table 1. The heat flux sensors disc (HFSD), located at the bottom of the pebble bed, has two sensors to measure the heat flux. In addition two thermocouples are integrated into this HFSD to measure its temperature. Another independent measurement of the heat flux may be obtained by the heat flux meter located below the HFSD. A heat sink was manufactured from copper solid cylinder and copper tube where flowing cold water, in the copper tube, enables the heat sink to provide the test article with a uniform cold temperature. The test article is placed inside a stainless steel chamber, called helium chamber, to control the pressure of the used gas (helium).

It is necessary to minimize the lateral heat losses because these losses disturb the one dimensional heat flow inside the pebbles bed and jeopardize the accuracy of the measurements. Therefore the helium chamber is placed inside a Pyrex bell jar, called vacuum chamber, in order to create vacuum around the helium chamber. In addition, radiation shields are located between the helium chamber and the vacuum chamber to reduce the heat loss by radiation. In addition to the main parts of the experimental apparatus presented in the above paragraphs, some auxiliary equipments were implemented to conduct the experimental tests. These auxiliary equipments include, but not limited to, mechanical pumps, data acquisition unit, personal computer, pressure gauges, vacuum feed through, helium cylinder, and cold water supply / drain system. Figure 2 shows a picture of the experimental apparatus with its auxiliary equipments.

TABLE I. Thermocouples specifications

| | |
|---|---|
| Thermocouple type | K |
| Sheath material | Inconel ($T_{max}$ = 1148°C) |
| Probe dimensions | D = 1.60mm, L = 203mm |
| Error | ±1.1°C or ±0.4% |
| Junction style | Ungrounded junction |
| Sensing $T_{max}$ | 950°C |

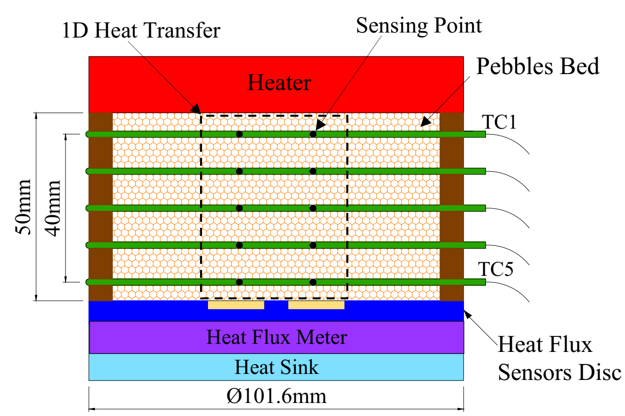


Fig. 1. The pebble bed and its thermocouples.

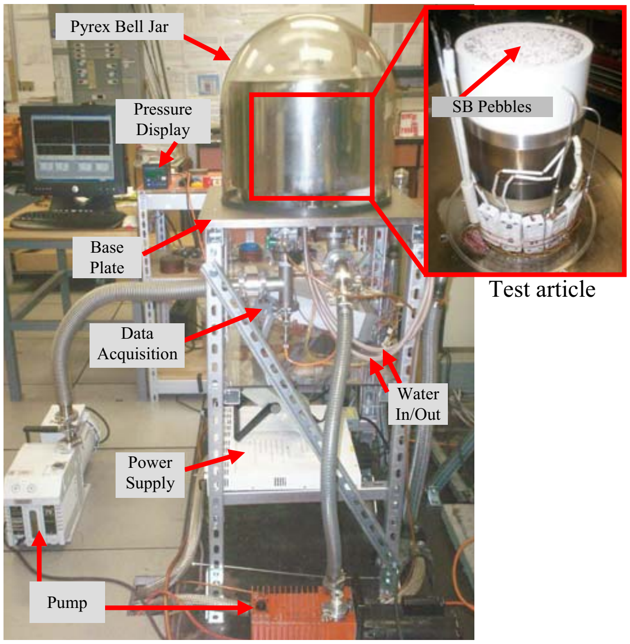


Fig. 2. The experimental apparatus.

## IV. DATA ANALYSIS

To determine the experimental value of *h* for the $Li_2TiO_3$ pebble bed, two steps are needed: (i) perform the experiment and store the measured data, taken after reaching the steady state condition, in a personal computer and (ii) use the measured data to calculate *h*. A temperature difference is observed at the interface of the pebbles with the containing wall where the measured wall temperature is smaller than the extrapolated pebbles temperature. The bed temperature profile is obtained by plotting the measured bed temperatures versus the corresponding distances measured from the pebbles/wall interface. The extrapolated pebbles temperature is determined by extrapolating the bed temperatures to the wall using a linear regression fit of temperatures. The extrapolated temperature ($T_e$) is compared with the measured wall temperature ($T_w$). Then the measured heat flux ($q$) is divided by the temperature difference ($\Delta T = T_e - T_w$) to give the value of *h*.

## V. RESULTS AND DISCUSSION

Figure 3 shows the experimental values of *h* of the lithium metatitanate pebble bed as a function of the wall temperature from 24 to 570°C. The pebble bed is single size (1.7-2.0mm diameter pebbles) with a packing fraction of 61%. Helium, at the atmospheric pressure, was used as a cover gas. The experimental results of this study show that *h* increased from 1800 to 5300W/$m^2$.K with the increase of the wall temperature from 24 to 570°C; i.e. *h* increased by a factor of 2.94 with the increase of temperature. At the interface between the pebbles and their containing wall, heat is transferred by: (i) conduction through the contact areas between the pebbles and wall, (ii) conduction through the intermediate gas, and (iii) radiation between the wall and the pebbles at high temperatures. Since the gaps between the contacting surfaces is very small (some microns), heat transfer by convection does not take place within these gaseous gaps.

It is noted that the thermal conductivity of helium (intermediate gas between pebbles and structure) increases nearly by a factor of two over the range of temperature considered. This may explain why the interface conductance increases with the increase of temperature. However, the increasing rate of *h* is larger than the increasing rate of the helium's thermal conductivity $k_{He}$ for the same temperature range. This shows that the increase of $k_{He}$ is not the only factor that contributes to the increase of *h* with temperature. Another contribution comes from the thermal conductivity of the wall ($k_w$) because it increases with the increase of temperature. The impact of $k_w$ on *h* can be seen in the calculations and results of Gorbis et al.[8] model. In addition, the radiation between the pebbles and wall is directly proportional to the temperature; therefore, with increasing temperature the radiation contribution increases. This also has a role in the increase of *h* with the increase of temperature. It is worth to mention that *h* was experimentally measured for wall's temperatures up to 570°C only because the maximum design temperature[6] of the wall structure is 550°C, therefore there is no need to make measurements beyond 550°C. Increasing the value of *h* with the increase of temperature is beneficial to the fusion blanket because this could reduce the temperature drop at the interface and consequently allowing higher temperature operation based on maintaining the solid breeder temperature within its allowable temperature window. Three models of predicting *h* of pebble beds were selected to compare their predictions with the present experimental results. These models (Schlünder[7], Gorbis et al.[8], and Yagi-Kunii[9]) are summarized in the following paragraphs.

Schlünder formulated the following equations for pebble beds filled with stagnant gas:

$$\alpha_{wp} = \frac{4k_g}{d}\left[\left(1+\frac{2l+2\delta}{d}\right)\ln\left(1+\frac{d}{2l+2\delta}\right)-1\right] \tag{1}$$

$$l = 2\sigma\left(\frac{2}{\gamma}-1\right) \tag{2}$$

Where $k_g$: thermal conductivity of the gas (W/m.K),
$\delta$: sum of the roughness of both surfaces (m),
$d$: average diameter of pebbles (m),
$\gamma$: accommodation coefficient, and
$\sigma$: mean free path of the gas molecules (m).
Then $h$ is calculated by including the effects of radiation and contact area as follows:

$$h=\varphi_A\,\alpha_{wp}+\frac{2(1-\varphi_A)k_g}{\sqrt{2}\,d+2l+2\delta}+\alpha_R+\alpha_{ws} \quad (3)$$

Where $\varphi_A$ is defined as the wall surface coverage factor and $\alpha_R$ takes into account the exchange of heat between the pebble and the wall by radiation.

$$\alpha_R=\frac{4C_s}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_s}-1}T_m^3 \quad (4)$$

$$\alpha_{ws}=\frac{2\rho_w k_s}{d} \quad (5)$$

Where $C_s$: Stefan-Boltzmann constant,
$k_s$: thermal conductivity of pebbles,
$\rho^2{}_w$: contact area between a sphere and the wall,
$T_m$: mean absolute temperature (K), and
$\varepsilon_s$ , $\varepsilon_w$: emissivity of packed bed and wall respectively.

Yagi and Kunii presented the following equations to calculate $h$:

$$h=\left[\frac{d}{k_g}\left(\frac{k_g}{k_w}-\frac{0.5k_g}{k_{eff}}\right)\right]^{-1} \quad (6)$$

$$\frac{k_w}{k_g}=p_w\left(2+\alpha_{rv}\frac{d}{k_g}\right)+\frac{(1-p_w)}{1/(1/f_w+\alpha_{rs}d/k_g)+k_g/3k_s} \quad (7)$$

$$f_w=\frac{0.25(1-k_g/k_s)^2}{\ln(k_s/k_g)+k_g/k_s-1}-\frac{k_g}{3k_s} \quad (8)$$

The heat transfer coefficients $\alpha_{rs}$ and $\alpha_{rv}$ are defined as:

$$\alpha_{rs}=\frac{0.04C_s T^3\varepsilon}{2-\varepsilon} \quad (9)$$

$$\alpha_{rv}=\frac{0.04C_s T^3}{1+p(1-\varepsilon)/[2(1-p)\varepsilon]} \quad (10)$$

Where $k_w$: thermal conductivity of wall,
$k_{eff}$: effective thermal conductivity of the pebble bed,
$T$: absolute temperature,
$\varepsilon$: emissivity of pebbles, and
$p$, $p_w$: porosity of pebble bed and near-wall region respectively.

Gorbis et al. model states that $h$ may be determined as follows:

$$\frac{hr}{k_g}=\frac{1.91(1-\varepsilon_w)}{\frac{\pi k_g}{6k_s}+\frac{k_g}{2k_m\rho_c+\frac{k_g(1-0.5\rho_c^2)}{0.477+2j/r}}}+\frac{1.91\varepsilon_w-0.91}{1+2j/r} \quad (11)$$

$$\rho_c=r_c/r \quad (12)$$

$$k_m=\frac{2k_s k_w}{k_s+k_w} \quad (13)$$

Where $k_m$: effective conductivity of contacting surfaces,
$r$: radius of pebble,
$j$: gas temperature jump distance, and
$\varepsilon_w$: porosity of the near-wall region.
The contact radius $r_c$ for a spherical pebble in contact with a flat surface is defined as:

$$r_c=\sqrt[3]{\frac{3}{4}Pr\left(\frac{1-\mu_s^2}{E_s}+\frac{1-\mu_w^2}{E_w}\right)} \quad (14)$$

Where $P$: contact force per pebble,
$E_s$, $E_w$: modulus of elasticity of pebbles and wall respectively, and
$\mu_s$, $\mu_w$: Poisson's ratio of pebbles and wall respectively.

Figure 3 shows the theoretical predictions of $h$ by the three selected models (Schlünder, Gorbis et al., and Yagi-Kunii) as well as the present experimental values of $h$ for the $Li_2TiO_3$ pebble bed. In general the predictions of the three models and the experimental values of $h$ have similar behavior with the increase of temperature. The predictions of Schlünder model are in good agreement with the experimental values of $h$ in the temperature range of 24 to 400°C; however beyond this range the Schlünder's predictions start to diverge from the experimental values. On the other side the predictions of

Gorbis et al. model are in good agreement with the experimental values of *h* within the temperature range of 350 to 570°C. Also, the slope of line formed by the points predicted by Gorbis et al. model is similar to the slope of line formed by the experimental points. Better agreement between the experimental results and the predictions of Gorbis et al. model may be achieved if the radiation between the pebbles and wall is taken into consideration. The Gorbis et al. model was derived based on some assumptions; one of them is to neglect radiation. Despite giving the same trend of *h* with temperature, Yagi-Kunii model under-predicts the values of *h* with a noticeable margin.

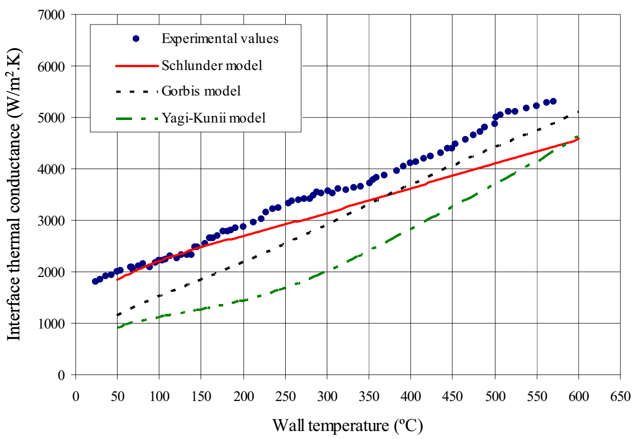


Fig. 3. Interface conductance of the $Li_2TiO_3$ pebble bed.

## VI. CONCLUSIONS

The conclusions of this study can be summarized in the following points:

- The experimental values of *h* increased from 1800 to 5300W/m$^2$.K with the increase of the wall temperature from 24 to 570°C.
- The experimental values of *h* were compared with theoretical predictions given by three models, namely; Schlünder[7], Gorbis et al.[8], and Yagi-Kunii[9]. The models predictions and the experimental values of *h* have similar behavior with the increase of temperature and the best predictions were given by Gorbis et al[8].
- The present results of *h* will help to build a reliable database of the thermal properties of lithium ceramics pebble beds, which is needed for the R&D of the fusion blankets.

## REFERENCES

1. Mario DALLE DONNE and GIANCARLO SORDON, "Heat Transfer in Pebble Beds for Fusion Blankets", *Fusion Technology*, **17**, 597 (1990).
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 a Mixed Bed of $Li_4SiO_4$ and Aluminum Pebbles", *J. Nuclear Materials*, **191-194**, 149 (1992).
3. FATOLLAH TEHRANIAN, and MOHAMED ABDOU, "Experimental Study of the Effect of External Pressure on Particle Bed Effective Thermal Properties", *Fusion Technology*, **27**, 298 (1995).
4. M. FERRARI, M. FURRER, G. SIMBOLOTTI, and C. TALARICO, "1-Pin Blanket Mockup: Results of the Extended Test Campaign", *Fusion Technology*, **30**, (1996).
5. http://www.zrci.com.
6. L. V. BOCCACCINI, J. D. LULEWICZ, G. PIAZZA, J. REIMANN, and N. ROUX, "Ceramic Breeder Pebble Beds for EU HCPB Test Blanket Module", *FZK Materials Assessment Report*, Karlsruhe, Germany, (2000).
7. E. U. SCHLUNDER, "Particle Heat Transfer", *Proc. 7th Int. Heat Transfer Conference*, Munchen, 195 (1982).
8. Z. R. GORBIS and M.S. TILLACK, F. TEHRANIAN, and M. ABDOU, "Analysis of Wall-Packed-Bed Thermal Interactions", *Fusion Engineering and Design*, **27** (1995).
9. S. YAGI and D. KUNII, "Studies on Heat Transfer in Packed Beds", *Proc. Int. Heat Transfer Conference*, Boulder, Colorado, **IV**, 750 (1961).