Fusion Science and Technology

ISSN: 1536-1055 (Print) 1943-7641 (Online) Journal homepage: http://ans.tandfonline.com/loi/ufst20

Transient Hot-Wire Experimental System for Measuring the Effective Thermal Conductivity of a Ceramic Breeder Pebble Bed

Christopher Kang, Yi-Hyun Park, Jon T. Van Lew, Alice Ying, Mohamed Abdou & Seungyon Cho

To cite this article: Christopher Kang, Yi-Hyun Park, Jon T. Van Lew, Alice Ying, Mohamed Abdou & Seungyon Cho (2017) Transient Hot-Wire Experimental System for Measuring the Effective Thermal Conductivity of a Ceramic Breeder Pebble Bed, Fusion Science and Technology, 72:3, 263-270, DOI: 10.1080/15361055.2017.1333830

To link to this article: https://doi.org/10.1080/15361055.2017.1333830

Published online: 30 Jun 2017.

FUSION SCIENCE AND TECHNOLOGY · VOLUME 72 · 263–270 · OCTOBER 2017

DOI: https://doi.org/10.1080/15361055.2017.1333830

Transient Hot-Wire Experimental System for Measuring the Effective Thermal Conductivity of a Ceramic Breeder Pebble Bed

Christopher Kang,[a]* Yi-Hyun Park,[b] Jon T. Van Lew,[a] Alice Ying,[a] Mohamed Abdou,[a] and Seungyon Cho[b]

[a]*UCLA, Mechanical and Aerospace Engineering Department, Los Angeles, California*
[b]*National Fusion Research Institute, Daejeon, Korea*

Received September 16, 2016
Accepted for Publication March 7, 2017

Abstract — *Characterizing the thermo-physical properties of the ceramic breeder pebble bed is an integral step of developing breeder blankets for fusion energy applications. To that end, thermal conductivity is an important parameter to identify. In granular pebble bed materials, the thermal conductivity depends on the solid pebble material as well as any gas filling the interstitial void spaces, thus an effective thermal conductivity (k_{eff}) of the bulk is used. A transient hot-wire apparatus is developed through a collaborative study between the Fusion Science and Technology Center at UCLA and the National Fusion Research Institute (NFRI) to measure the effective thermal conductivity of Korean-made Li_2TiO_3 pebble beds. In this study, current is pushed through a single strand of high purity platinum wire. The heat generated is conducted away by the surrounding pebble bed; the logarithmic change in temperature being used to calculate the rate of heat conductance. The apparatus is filled with roughly an atmosphere of helium and placed in a furnace to test the pebble bed under reactor relevant temperatures. Results and future improvements are presented.*

Keywords — *Pebble bed, transient hot-wire, lithium metatitanate.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Pebble beds of lithium-oxide ceramics satisfy many of the design requirements for generating tritium in a self-sustaining fuel cycle in a fusion reactor.[1] Several demonstration power-production fusion reactors (DEMO reactors) are under pre-conceptual design incorporating ceramic pebble beds. Consequently, lithium ceramic pebble beds are being tested by nearly every participating party, in the international experiment ITER, for their capabilities and performance.

Owing to the temperature dependence of mechanics governing tritium release from ceramic pebble beds, the ability for these pebble beds to reliably and predictably maintain operation within designated temperature windows is critical for the success of the solid breeder concept.[2] The two-phase medium of interstitial helium purge gas and ceramic solid can be considered as a single fictitious continuum medium with effective material properties. Measures of effective thermal conductivity, k_{eff}, of virgin (*i.e.*, unirradiated, non-thermally-cycled) pebble beds are the first step toward predictive capability of solid breeders. Experimental approaches for measuring k_{eff} have historically fallen into one of two categories: transient or steady-state.[3–8] Having reviewed the characteristics of the two methods, in the current work we have adopted the transient hot-wire (THW) approach to measure the effective thermal conductivity of Li_2TiO_3 pebbles produced by National Fusion Research Institute (NFRI). NFRI has recently developed the Slurry Droplet Wetting Method,[9,10] and pebble beds from the newly-developed process must be characterized. The experimental measurement of effective thermal conductivity of

*E-mail: chris@fusion.ucla.edu

Li_2TiO_3 pebble beds has been carried out at UCLA as part of a collaborative effort between UCLA and NFRI.

By observing temperature change as a function of logarithmic time, a linear region develops from which the thermal conductivity of the material may be inferred. Similar to the work of Ishido et al. a conductive wire is run through the test bed to produce transient heating characteristics.[11] However, in terms of instrumentation effects on pebble beds, *i.e.*, thermocouple probe disruption of bed packing, no standardized method exists and care must be taken to eliminate disturbances to the test article due to instrumentation. To mitigate these concerns, we have adopted the so-called "Resistance Technique" or "4-Wire Technique" for which the hot wire acts as both the heating element as well as the temperature sensor.[12,13] A major study on the geometric influences of the THW experimental container was done by Christopher.[14] The UCLA-THW apparatus was built to adhere to those constraints.

The remainder of this paper is organized as follows: In Sec. II, a description of the background of the method, the design, and implementation of the UCLA test article will be presented. Section III describes the experimental conditions and presents the results of the study. A discussion can also be found therein. Section IV summarizes the efforts made in this paper as well as some planned future work.

II. DESCRIPTION OF EXPERIMENTAL APPARATUS

The experimental platform must recreate, as close as possible, the initial conditions and physical assumptions used in design analysis. To measure the bulk thermal conductivity, a 1-dimensional heat flux is required. Due to inherently low thermal conductivity of ceramic pebble beds, one-dimensionality of temperature distributions is one of the most challenging aspects of experiment design and great care was taken to ensure control of oven heating. Furthermore, the integration of sensors must also be done with minimal disruption to the pebble bed packing structure to avoid non-representative conditions. The THW experiment aims to address many of these challenges.

II.A. NFRI Li_2TiO_3 Pebbles

Lithium-based ceramics are strongly considered for their neutron and tritium generating capabilities. Of the possible lithium-based chemistries, lithium metatitanate is the material choice of NFRI. Some of the advantages include high mechanical strength and chemical stability.

A detailed discussion of the fabrication process of the pebbles are outside the scope of this work, and refer the reader to the works of Park et al.[9,10] Still, as the physical properties of the individual constituent pebbles translate to the bed behavior, it is relevant to briefly mention some of the associated material properties in Table I.

II.B. UCLA Design of Experimental Apparatus

The test apparatus is designed in general accordance to established hot-wire measurement theory.[15,16] Established for continuum test materials, *e.g.*, refractory bricks, a wire is installed down the centerline of the material of interest. This wire is used to provide a constant source of heat into the material through resistive heating. The mathematical model, assuming one-dimensional heat flow through radius, r, is

$$\Delta T = \frac{1}{k_{\text{eff}}} \cdot \frac{q}{4\pi} \cdot \ln\left(\frac{4\kappa t}{r^2 C}\right) = \frac{1}{k_{\text{eff}}} \cdot \frac{q}{4\pi} \cdot (\ln(t) + A) , \quad (1)$$

where in the simplified result, ΔT is the change in temperature, t is time, κ the thermal diffusivity of the medium, C the thermal capacitance, and q is the applied heat per length of the wire $[\mathrm{W\,m^{-1}}]$. It is important to state that the heat generated in the wire is assumed uniform along its length, and the geometric aspect ratios are sufficient to neglect "edge effect" contributions.

In a logarithmic scale, Eq. (1) is of a linear form as $\Delta T = mt + b$, where the slope is

$$m = \frac{q}{4\pi\, k_{\text{eff}}} . \quad (2)$$

TABLE I

Container and Pebble Properties

UCLA-THW		
Chamber Length	203.2	mm
Chamber Diameter	60.2	mm
Wire Length	127.0	mm
Pebble Volume	578.4	mL
KO NFRI Li_2TiO_3 Pebbles		
Average Diameter	1.03	mm
Average Grain Size	10	μm
Sinter Temperature	1000	°C
Average Crush Load	33	N
Density	3.1	$\mathrm{g\ cm^{-3}}$
Open Porosity	7.5	%
Closed Porosity	2.5	%

One advantage of the current 4-Wire Technique is that through the use of computer controlled data acquisition hardware, we may simultaneously introduce power as well as measure the system temperature. Sampling rates of measurements should be sufficiently fast to capture the transient dynamics of heat transfer into the test medium. Then from measurement of time and temperature rise, k_{eff} is extracted from the slope of measurement data.

For breeder pebble bed applications specifically, the transient hot-wire method has been successfully applied for Li_4SiO_4 (Ref. 17) and Li_2TiO_3 (Ref. 6), among others. Yet, these methods employed the traditional hot-wire method of using thermocouples to provide temperature bed measurement. Since the test medium investigated in this work consists of loosely packed pebbles, the addition of sensing equipment can introduce local non-homogeneities. In other words, in a loosely packed pebble bed when transient measurements are required, it is difficult to ensure robustness of measurement; whether the tip of the thermocouple is measuring a pebble, a void, or whether solid contact exists.

To minimize these disturbances, the 4-Wire Technique variation of the hot-wire method is employed.[12,13] Leveraging a well-known property of conductive metals, the heating wire of THW can be used to measure the temperature as well. Simply put, the resistance of metals change as a function of its temperature. For platinum, this change in resistance is quite linear in the operational temperature region. By applying current to the loop, well-placed voltage tie-ins are used to measure the voltage drop across the platinum wire, which is then used to calculate the transient temperature profile of the hot-wire. Furthermore, the 4-wire setup is also advantageous in laboratory settings because it is insensitive to effects from such things as mixed gauges, mixed lengths, or resistance changes of lead wires. For instance, though the measurement wires experience steep thermal gradients along its length as it passes through the vacuum access ports, the setup is oblivious to these changes and measures only the voltage drop across the hot-wire.

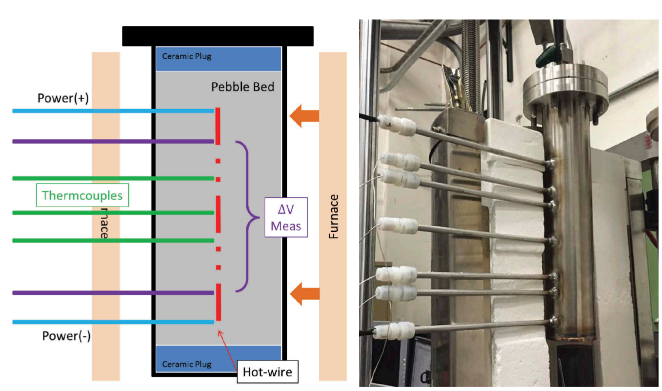
Platinum wire of 99% purity is strung between two power connectors. These ports are connected to a computer-controlled power supply which is used to provide regulated current for the experiment. A cylindrical housing is ideal for uniform heat dissipation in the radial direction. To study the bed at reactor relevant conditions, the module is also designed to be incorporated within a clam-shell furnace, for elevated bed temperatures, as well as a 1 atm helium environment. Once placed in the furnace, instrumentation must be passed through the main body of the THW apparatus while maintaining tight sealing to prevent helium outgassing.

Christopher studied the effect the geometry of the test apparatus had on the resulting measurements.[14] Several length-scale ratios were important to maintain to keep the simplifying assumption valid. For example, a longer bed length compared to its diameter meant that most of the heat flow could be assumed 1-dimensional in the radial direction, relative to axial direction. The relevant dimensions of the designed experimental apparatus are provided in Table I.

The apparatus is constructed of 304 Stainless with instrumentation thru-ports welded down the barrel. Through these ports, electrical power for the hot-wire, voltage leads for measurement, and thermocouple access points for diagnostics are connected. To better depict internal details, Fig. 1a shows a schematic cross-sectional representation of the experimental apparatus. A variable programmable power supply connected to the outer-most pair of thru-ports provides the necessary current. The voltage drop, a temperature dependent function of the resistivity of platinum, is measured across the wire using a standard A/D data acquisition unit. Additional thru-ports allow thermocouples to be inserted into the bed at varying radial depths for diagnostic or calibration purposes. The entire apparatus is prepared and placed into a clam-shell furnace, shown in Fig. 1b.

III. EXPERIMENT

Experiments were conducted on the NFRI Li_2TiO_3 pebbles. These tests were designed to measure the effective thermal conductivity of a packed pebble bed at



(a) Schematic (b) THW in Furnace

Fig. 1. UCLA-THW apparatus.

elevated temperatures, including temperatures near breeder reactor relevant conditions, *i.e.*, 500°C–1000°C.

III.A. Experiment Setup

The general procedure is as follows: the apparatus is filled with pebbles, vibration packed, charged with helium, then sealed and placed in the furnace. Since the volume of the chamber is known, the quantity of pebbles required to achieve a 63% packing fraction is determined by mass. Generally, any packing fraction >63% is desired by design. A cylindrical plug of low thermal-conductivity ceramic is placed in the chamber between the pebble bed and lid (Fig. 1a). The height of the plug is accurately cut so that when the desired packing fraction is achieved, the lid sits flush with the flange and can be closed. This plug also reduces helium convection in the chamber; an effect isolated in the current approach. A bake out procedure is also performed to remove moisture from the system, as needed. The test article is pumped to vacuum (approximately 3Pa), then filled with helium. A pressure of 0.1 MPa is desired during the experiment. In the current iteration of the experimental apparatus design, no on-line monitoring or pressure regulation is available. Because helium charging is done at room temperature, we apply Gay-Lussac's Law for ideal gases to determine the initial helium pressure. Future design improvements include high-temperature helium gas pressure measurement and control; possibly incorporating a flowing purge gas scheme.

Because the calculation and processing of the measurement is performed on a transient phenomenon, it is critical to record data at regular intervals as well as synchronize events against a clock. To achieve this, LabVIEW was used to acquire measurements through a DAQ at a 1 Hz rate. It was also the interface to control the programmable power supply used to apply the necessary current to the hot-wire at the onset of the transient experiments.

During heating in the furnace, the temperature of the pebble bed, by way of the platinum wire is monitored via a trickle current; a mA-range current large enough to register a voltage measurement without greatly heating itself. Thermocouples attached to the container are simultaneously monitored and are used to close the feedback loop to control the heating supplied by the furnace. Steady-state is considered achieved when these external thermocouples controlling the furnace along with platinum wire have all sufficiently stabilized about their temperature set-points. By comparing the stabilized values of the external thermocouples to the reading taken at the center of the bed (via platinum wire), bed temperature uniformity is assumed.

To begin the experiment, a constant current is then pumped through the platinum wire. This elevates the temperature of the wire relative to the pebble bed. As heat flows out of the wire into the surrounding pebble bed, the change in resistance of the platinum wire is measured, processed, and the temperature of the wire can be extracted.

Once the hot-wire is activated, its temperature begins to rise logarithmically. An example data set is show in Fig. 2 for illustrative purposes. When shown in semi-logarithmic scaling of the time-axis, the linear portion of the data (highlighted), is used to recover the slope to be used in Eq. (2) to determine k_{eff}. If the temperature increase was a purely logarithmic function, the entire time trace would sit on a perfect line in logarithmic time. However, the data points immediately following the power supply trigger-on as well as data points near the end of the data collection exhibit deviations from this fit. These effects are attributed to such causes as the wire reaching a stable and constant power (at the beginning) and the heat becoming influenced by wall-effects (near the end), among others. As such, a general iterative process is used to capture only the most linear region in the regression; utilizing the highlighted regions in both linear- and logarithmic-time to serve as visual guides. At each background temperature, several pulses (runs) are conducted to establish a statistical average. There is a refractory period; the pebble bed must be allowed to return to the background temperature.

III.B. Results

Experiments have been completed at seven temperature set points. For the elevated temperatures between 300°C and 800°C the averaged k_{eff} of the pebble bed are tabulated in Table II. At these elevated temperatures, the effective conductivities are near a value of 1.1 W m^{-1} K^{-1}.

Due to the current limitations of the setup to regulate the helium pressure *in situ*, each temperature set point would require a helium fill at RT, requiring the cooling of the set up. Yet, cooling of the bed will introduce another variable into the study, namely resettling of the pebble bed due to thermal cycling. To maintain comparable test conditions, once the apparatus was cooled, it was also disassembled and the pebble bed re-packed to the original packing configuration. This also allowed for the opportunity to observe any macro-scale changes to the bed (*e.g.*, bed color and bed sintering). This procedure ensures that

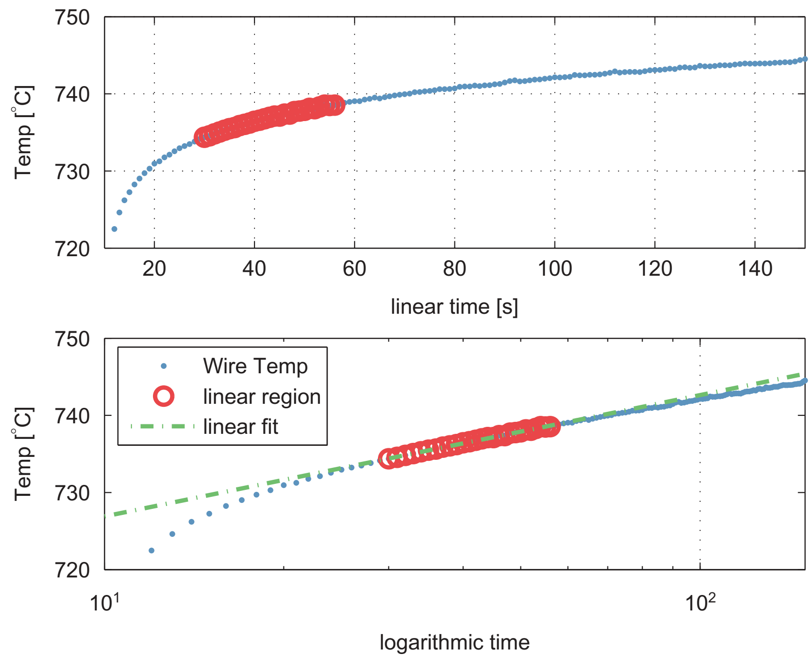


Fig. 2. Sample measurement data of Pt wire in pebble bed.

TABLE II

k_{eff} of NFRI Li_2TiO_3

Average Temp. °C	Average k_{eff} W m^{-1} K^{-1}	Standard Error
23.3 [RT]	0.75	0.022
310.2	1.11	0.019
398.8	1.15	0.009
503.9	1.12	0.020
606.1	1.14	0.014
697.8	1.06	0.033
803.8	1.24	0.006

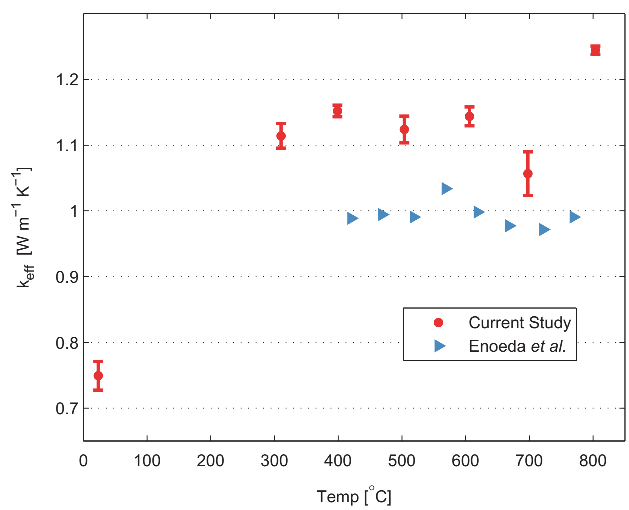


Fig. 3. k_{eff} of KO NFRI Li_2TiO_3 compared to Enoeda et al.

these results represent the averaged thermal conductivities for the first thermal cycle for beds that share the same initial RT packing conditions.

1. *Discussion*: At 63% packing fraction, k_{eff} at room temperature is relatively low. Without the aid of thermal expansion of the pebbles, there may be comparatively low contact between neighboring pebbles to facilitate strong conduction. Still, this data-point could be well considered academic as it is well outside the nominal operating range of a breeder blanket. At the elevated temperatures, the measured thermal conductivity is higher and slightly increases with temperature, as seen in Fig. 3. This behavior can be hypothesized as a dynamic interaction of a few known phenomena. Though it has been reported that thermal conductivity of Li_2TiO_3 decreases as a function of temperature in this range,[18] the conductivity of stagnant helium is also known to increase as a function of temperature.[19] Also, effective thermal expansion of Li_2TiO_3 pebble beds are approximately 14×10^{-6} K^{-1} over the temperatures of interest to this study,[20] while α of 304 Stainless is generally larger, around 17×10^{-6} K^{-1}. While the pebble bed is packed well at room temperature, expansion of the equally-hot container at high temperatures may relieve pressure on the pebbles and in fact reduce the effective conductivity. Nevertheless, all combined, the net effect of these interactions is the slight increase of k_{eff}.

As a quantitative measure of precision of the data, the standard error is calculated at each temperature. For all, the standard error is roughly 1% of the measured value, indicating good confidence in the repeatability of each experiment. The data, as reported in Table II, shows a slight increase in spread for the room temperature and 700°C measurements. This will be further expanded on in the following subsection.

An interesting observation to note is the apparent dip in k_{eff} at 700°C before rising again at 800°C. Great care was taken to ensure that this data set was accurate including repeating several setups and performing diagnostics of the equipment. At present, this result can only be attributed to the combination of the multiple competing physical phenomena in the system. Comparison between the work of Enoeda et al. and this study, in Fig. 3, shows a similar trend in k_{eff} as a function of temperature, a slight increase with temperature with a dip near 700°C, though with a less-pronounced dip compared to what was observed in this study.[21] However, the cause has never been discussed. Since details of their experimental design are not known, no direct comparison can be made. Their entire data set also shows a lower magnitude across all tested temperatures. It could be the case that a comparatively thicker hot-wire may have been used, producing the lower k_{eff} measurements, the justification to be expanded in the following subsection.

It is a secondary intent of this paper to disclose all these relevant parameters to allow future studies to directly compare against this study; detailing the critical parameters which contribute non-negligible effects on the measurement.

2. *A Study on Hot-Wire Diameter*: Originally, the THW apparatus was built with 27 Gauge platinum wire with the aim of minimal disruption to bulk packing using a thinner wire. The apparatus functioned well up to 600°C; above this temperature the thermal stresses of expanding pebbles repeatedly broke the wire and caused an open circuit in the measurement. To address this issue, a thicker 24 Gauge platinum wire was adopted for higher temperature tests. Measurements at 700°C and 800°C were done with 24 Gauge wire.

Tests were performed to measure k_{eff} with the two gauges of wire to determine the impact of wire choice on measurements; thickness of wire may effect surface contact with pebbles or cause different packing structures. Temperature sets were repeated for Room Temp and 600°C and shown graphically in Fig. 4.

At room temperature and 600°C, using the thicker gauge hot-wire reduced the measured k_{eff} by roughly 14% and 6%, respectively. Presenting these sets together resulted in the slightly higher standard error reported in Table II, though each measurement set for each wire thickness had similarly tight *precision*. Such observation provides our rationale for the possible discrepancy in k_{eff} between this study and Enoeda.

IV. CONCLUSION

NFRI has produced Li_2TiO_3 pebbles with a new Slurry Droplet Wetting Method. Efforts were made to experimentally characterize the effective thermal conductivity of a pebbled bed comprised of these pebbles. A custom transient hot-wire apparatus was designed and

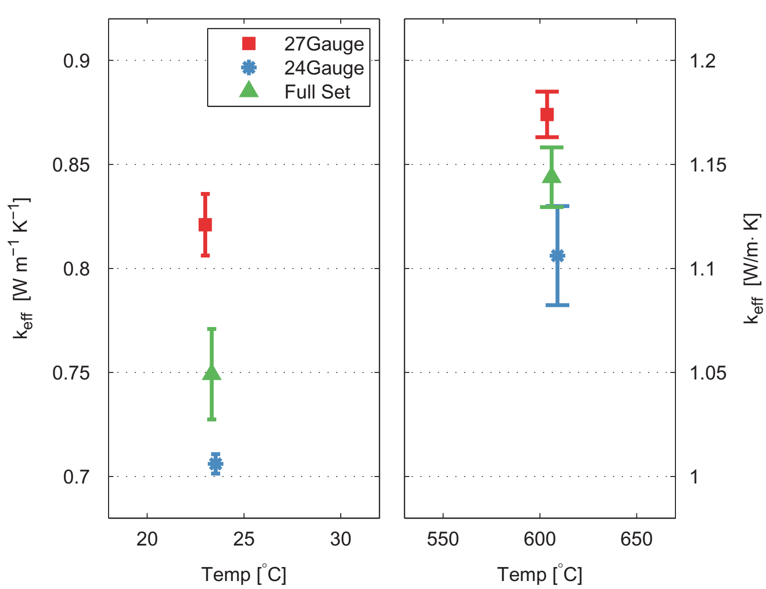


Fig. 4. Effect of hot-wire gauge.

fabricated to facilitate testing of these pebble beds at high temperature. Due to the size of the pebbles (1 mm), relative to the instrumentation, the 4-Wire Technique of the Transient Hot-Wire method was utilized to minimize bed disruption. In a stagnant helium environment, several tests were performed at different temperature settings, and the resulting k_{eff} values were calculated and presented. The resulting trends agree well with comparable material pebble bed studies; without more explicit knowledge of the various setups (*e.g.*, chamber aspect ratio, pebble diameters, etc.) we can draw no direct comparison.

Future efforts include designing apparatuses and testing these pebbles in environments that more closely mimic the breeder blanket bed environment. Factors to consider include, flowing helium and differential stresses on beds due to steep temperature gradients between the core of the bed and cooler structure. In this study, the pressure exerted on the pebble bed from the structure is not measured. Relief of pressure due to larger thermal expansion of the container was not studied in detail and should be considered in the future. Furthermore, the current iteration of the THW does not measure the interface heat conductance, another important thermo-physical parameter to quantify in ceramic pebble beds.

Lastly, a study was performed to consider the effects of hot-wire diameter on measured values of k_{eff}. At two temperature points of 25°C and 600°C, small reductions in effective conductivity were seen when larger diameter hot-wire was used of 14% and 6%, respectively. The difference is attributed to altered contact behavior with thicker wire. Numerical models of pebble-scale interaction may provide insight on the link between heat transfer and micromechanical interactions inside pebble beds; efforts to develop such numerical models are under development at UCLA.

Acknowledgments

This work was supported by the U.S. Department of Energy Contract DE-FG03-ER52123.

References

1. R. CLEMMER, "The Development of Tritium Breeding Blankets for DT-Burning Fusion Reactors," *4th ANS Topical Mtg. on the Technology of Controlled Nuclear Fusion*, 1980.
2. M. ABDOU et al., "Blanket/First Wall Challenges and Required R&D on the Pathway to DEMO," *Fusion Eng. Des.*, **100**, 2 (2015); https://doi.org/10.1016/j.fusengdes.2015.07.021.
3. G. PIAZZA et al., "Measurements of Effective Thermal Conductivity of Ceramic Breeder Pebble Beds," *Fusion Eng. Des.*, **58**, 661 (2001); https://doi.org/10.1016/S0920-3796(01)00521-X.
4. M. DALLE DONNE et al., "Measurements of the Effective Thermal Conductivity of a Li_4SiO_4 Pebble Bed," *Fusion Eng. Des.*, **49**, 513 (2000); https://doi.org/10.1016/S0920-3796(00)00261-1.
5. T. HATANO et al., "Effective Thermal Conductivity of a Li_2TiO_3 Pebble Bed for a DEMO Blanket," *Fusion Sci. Technol.*, **44**, *1*, 94 (2003); https://doi.org/10.13182/FST03-A316.
6. H. TANIGAWA et al., "Effective Thermal Conductivity of a Compressed Li_2TiO_3 Pebble Bed," *Fusion Eng. Des.*, **75**, 801 (2005); https://doi.org/10.1016/j.fusengdes.2005.06.104.
7. H. TANIGAWA et al., "Thermal Conductivity Measurement with Silica-Coated Hot Wire for Li_4SiO_4 Pebble Bed," *J. Nucl. Sci. Technol.*, **46**, *6*, 553 (2009); https://doi.org/10.1080/18811248.2007.9711561.
8. Y. LI et al., "Design and Research on the Measurement Platform of the Effective Thermal Conductivity for Li_4SiO_4 and Li_2SiO_3 Pebble Bed," *Fusion Eng. Des.*, **98**, 1911 (2015); https://doi.org/10.1016/j.fusengdes.2015.02.061.
9. Y. H. PARK et al., "Fabrication of Li_2TiO_3 Pebbles Using PVA–Boric Acid Reaction for Solid Breeding Materials," *J. Nucl. Mater.*, **455**, *1*, 106 (2014); https://doi.org/10.1016/j.jnucmat.2014.05.027.
10. Y.-H. PARK et al., "Optimization of Mass-Production Conditions for Tritium Breeder Pebbles Based on Slurry Droplet Wetting Method," *Fusion Eng. Des.*, **109–111**, **Part A**, 443 (2016); https://doi.org/10.1016/j.fusengdes.2016.02.084.
11. Y. ISHIDO et al., "Thermal Conductivity of Magnesium-Nickel Hydride Powder Beds in a Hydrogen Atmosphere," *Int. J. Hydrogen Energy*, **7**, *2*, 173 (1982); https://doi.org/10.1016/0360-3199(82)90144-6.
12. S. ANDRÉ et al., "Hot Wire Method for the Thermal Characterization of Materials: Inverse Problem Application," *Engenharia Térmica*, **4**, 55 (2003); http://dx.doi.org/10.5380/ret.v2i2.3470.
13. J. HEALY et al., "The Theory of the Transient Hot-Wire Method for Measuring Thermal Conductivity," *Physica B+C*, **82**, *2*, 392 (1976); https://doi.org/10.1016/0378-4363(76)90203-5.
14. M. D. CHRISTOPHER, "Application of the Transient Hot-Wire Technique for Measurement of Effective Thermal Conductivity of Catalyzed Sodium Alanate for Hydrogen Storage," Ph.D. Thesis, Virginia Polytechnic Institute and State University (2006).
15. L. VOZÁR, "A Computer-Controlled Apparatus for Thermal Conductivity Measurement by the Transient Hot

Wire Method," *J. Therm. Anal. Calorim.*, **46**, *2*, 495 (1996). https://doi.org/10.1007/BF02135027.

16. ASTMC1113/C1113M, "Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique)" (2013); https://www.astm.org/Standards/C1113.htm (current as of September 16, 2016).
17. J. REIMANN and S. HERMSMEYER, "Thermal Conductivity of Compressed Ceramic Breeder Pebble Beds," *Fusion Eng. Des.*, **61**, 345 (2002); https://doi.org/10.1016/S0920-3796(02)00165-5.
18. S. SAITO et al., "Density Dependence on Thermal Properties of Li_2TiO_3 Pellets," *J. Nucl. Mater.*, **253**, *1*, 213 (1998); https://doi.org/10.1016/S0022-3115(97)00314-0.
19. H. PETERSEN, "The Properties of Helium: Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressures from 1 to 100 Bar and from Room Temperature to about 1800 K," Tech. Rep. (1970); http://orbit.dtu.dk/files/52768509/ris_224.pdf (current as of September 16, 2016).
20. H. TANIGAWA et al., "Measurement of Thermal Expansion of Li_2TiO_3 Pebble Beds," *Fusion Eng. Des.*, **82**, *15*, 2259 (2007); https://doi.org/10.1016/j.fusengdes.2007.06.023.
21. M. ENOEDA et al., "Effective Thermal Conductivity Measurement of the Candidate Ceramic Breeder Pebble Beds by the Hot Wire Method," *Fusion Technol.*, **39**, *2*, 612 (2001).