Fusion Engineering and Design 127 (2018) 34–39

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Experimental measurement and numerical modeling of the effective thermal conductivity of lithium meta-titanate pebble bed

Maulik Panchal[a,*], Christopher Kang[b], Alice Ying[b], Paritosh Chaudhuri[a]

[a] Institute for Plasma Research, Bhat, Gandhinagar, 382428, India
[b] UCLA, MAE Department, Los Angeles, CA 90095-1597, USA

ARTICLE INFO

Keywords:
Effective thermal conductivity
Li_2TiO_3 pebble bed
Packing structures
IN LLCB TBM

ABSTRACT

The effective thermal conductivity (k_{eff}) of lithium meta-titanate (Li_2TiO_3) pebble beds under fusion relevant environments is an important property for the design of IN LLCB TBM (Indian Lead Lithium Ceramic Breeder Test Blanket Module). The transient hot wire technique was used to examine the thermal property of the Indian made Li_2TiO_3 material. The hot wire is used as both the heating element as well as for the temperature measurement. The k_{eff} of Li_2TiO_3 pebble bed has been investigated from room temperature to 800 °C. Experiments were performed on uncompressed Li_2TiO_3 pebble bed in stagnant helium gas filled at ambient pressure. A clear dependence of the k_{eff} on the temperature of the pebble bed was observed. The pebble bed has pebbles of 1 ± 0.15 mm diameter and packing fraction of 63%. The experimental results showed that the k_{eff} increased from 0.903 W/m°C to 1.204 W/m°C with the increase of bed temperature from 34.3 °C to 785.4 °C. The random close packing of poly dispersed Li_2TiO_3 pebble bed has been generated using discrete element method and then numerical modeling has been performed using finite element method to estimate k_{eff}. The numerically determined k_{eff} of the Li_2TiO_3 pebble bed agrees reasonably well with the obtained experimental data. The experimentally achieved k_{eff} results are also compared with the reported experimental results elsewhere and also with Zehner–Schlunder correlation.

1. Introduction

Lithium meta-titanate (Li_2TiO_3) is considered as a promising tritium breeding material due to its properties like reasonable lithium atom density, prominent tritium release rate at low temperature, low activation characteristics, and low thermal expansion coefficient. India has proposed the Lead Lithium Ceramic Breeder Test Blanket Module (LLCB TBM) concept to be tested in the International Thermonuclear Experimental Reactor (ITER). LLCB TBM consists of Li_2TiO_3 as ceramic breeder material in the form of packed pebble beds and alloy lead-lithium eutectic (Pb–Li) as tritium breeder, neutron multiplier, and coolant for the ceramic breeder zones. Reduced activation ferritic martensitic steel (RAFMS) is used as the structural material for the first wall, which is actively cooled by high-pressure helium gas. Low-pressure helium gas is purged inside the ceramic breeder pebble bed zones to extract the generated tritium [1]. The Pb–Li flows separately around the ceramic breeder pebble bed canisters to extract heat generated from nuclear heating; transferring heat from the hot ceramic pebble beds to the coolant. The use of ceramics in pebble form has been the preferred option in most blanket designs due to its potential advantages like simpler assembly of breeder into complex geometry regions, uniform and stable pore network for purge gas transport, no thermal stress cracking because small thermal gradient across each pebbles, and active control of k_{eff} of bed by varying the purge gas pressure [2]. k_{eff} of Li_2TiO_3 pebble beds is an important design parameter for temperature control in the pebble beds.

The k_{eff} of pebble beds is influenced by many parameters to different degrees. Some of these parameters have significant impact on k_{eff} of the pebble beds, such as the thermal conductivities of the pebble material and purge gas, gas pressure, pebble bed deformation, and bed packing fraction. Other parameters have less impact such as pebble size and pebble surface roughness [3]. The contact area between pebbles directly affects the amount of heat flux across it, especially for pebble beds with high pebble to gas thermal conductivity ratio. When the pebbles are subjected to compressive stress, large enough to cause deformation, the contact area increases and consequently more heat is expected to flow through it. It has been observed that k_{eff} of Li_2TiO_3 pebble beds increases by 3% with compressive strain of 1% in a temperature range of 600 °C − 700 °C [4]. Several studies have been dedicated to investigate the k_{eff} of the lithium ceramics pebble beds.

* Corresponding author.
E-mail address: maulikpanchal@ipr.res.in (M. Panchal).

https://doi.org/10.1016/j.fusengdes.2017.12.003
Received 2 June 2017; Received in revised form 14 October 2017; Accepted 6 December 2017

Transient hot wire techniques [4–9] and steady state techniques [10,11] were applied to estimate the k_{eff} of different lithium ceramic breeder materials. Pebble beds can be considered as a heterogeneous solid-gas or two-phase system through which heat is transferred by different modes: conduction, convection, and radiation. The relative contribution of each mode of heat transfer changes with the working condition and thermal properties of pebble beds and can be conceptually considered to occur through a number of series and parallel thermal paths. The main contributors to the three modes are identified. First, conduction: (i) conduction internally through either solid or gas, (ii) conduction between gas and pebbles at interfaces, and (iii) conduction through contact areas of neighboring pebbles. Second, radiation: (i) radiation between adjacent pebble surfaces, and (ii) any possible emission/absorption by gas. And third, the advective mode of heat transfer for any gas in motion, with motion arising from: (i) imposed pressure gradients causing bulk flow, and (ii) buoyant forces from temperature gradients. The objective of this work is to measure the k_{eff} of Indian-fabricated Li_2TiO_3 pebble bed using the transient hot-wire technique. Temperature influence on the k_{eff} of Li_2TiO_3 pebble beds with stagnant helium gas was examined. This work has been carried out at UCLA, USA as a part of collaborative research agreement between IPR, India and UCLA, USA. Section 2 explains in detail about the experiments.

The numerical simulations using Finite Element methods [12–16] have been previously performed in detail to predict the k_{eff} of candidate of ceramic breeder pebble beds. In present study, the numerical simulations have also been performed to estimate k_{eff} of Li_2TiO_3 pebble bed under stagnant helium gas using the Finite Element Analysis (FEA) code, COMSOL [17]. As far as the fusion blanket pebble bed bulk region is concerned, conduction and radiation are the dominant mechanisms of the heat transfer inside the pebble bed. Purge gas Reynolds numbers are designed to be very small in solid breeder blankets (Re ~ 1), therefore advection contribution is negligible compared with the conduction contribution in pebble beds [18]. Moreover, the Darcian Rayleigh number in solid breeders is negligibly small (Ra ~ 10^{-5}) compared to the critical Darcian Rayleigh (Ra ≈ 40), therefore natural convection is not considered [19]. The details of the numerical modeling have been explained in Section 3. The numerically predicted k_{eff} of randomly close packed poly-dispersed Li_2TiO_3 pebble bed is compared with the value obtained from experiment in Section 4.

2. Experimental

An experimental setup has been designed by Christopher Kang [8] based on the transient hot-wire techniques for the measurement of k_{eff} of pebble beds. Fig. 1(a) shows the experimental setup developed for the k_{eff} measurements. The hot wire is made from 99% pure platinum material with 0.5 mm in diameter. The hot wire assembly is prepared outside the chamber as shown in Fig. 1(b). First, the hot wire is strung between two wire holders. A threaded rod is also passed through the same wire holders to keep the hot wire perfectly straight. At this stage, both the power connectors are not connected to the wire holders. After preparing this, the hot wire with help of the threaded rod is placed inside the chamber and then two power connectors are passed from outside to the chamber via the provided ports in such a way that it can hold both the wire holders with help of tightening threads. After holding the wire holders properly with help of the two power connectors a threaded rod is then removed from top side of chamber. It is important to keep the exact length of the hot wire in order to avoid any mismatch with the length between the provided ports on the chamber. Two additional wires are tied onto the hot-wire, between the two power connectors as shown in Fig. 1(b), to measure the voltage drop across the hot-wire. Additional temperature measurements of the pebble bed were collected with type K thermocouples. The sheath of thermocouple is made from stainless steel. The thermocouple sheath diameter and length is 1 mm and 200 mm, respectively. The tip of all three thermocouple is inserted in pebble bed from the outside via ports only up to 1–2 mm depth so that the high conductive material of thermocouple sheath cannot affect the heat transfer in pebble bed. Dimension influences for the transient hot wire experimental set up has been examined in detail by Christopher [20]. The present set up dimension is selected from that reference so that the end effects are sufficiently far from the measurement region. The wire is kept at the center axis of cylinder volume. For a homogeneous volume of material, heat flow from wire will be only in redial direction. During operation, the hot-wire is energized using a power supply. The hot-wire heats up due to Ohmic heating. This heat is conducted outward through the pebble bed, which allows for the study of k_{eff}. The height and inner diameter of stainless steel chamber is 300 mm and 60.2 mm, respectively. The height of pebble bed is 203.2 mm. Thermal insulation disks were placed inside cylinder at top and bottom of the pebble bed to minimize heat losses. The power ports are connected to a computer controlled variable power supply which is used to provide regulated current to the hot wire. The power supply is controlled via LabVIEW software interface. Regulated control of the current is important to ensure specified conditions are maintained through the experiment, as well as providing time-synchronized measurements which are critically important to the analysis of collected data. An Agilent data multiplexer, communicated via LabVIEW is used to measure the various sensors in the experimental system including the voltage drop across the hot-wire and thermocouples.

Once the fittings, welds, and other junctions were satisfactorily tested, the cylinder volume was filled with pebbles as shown in Fig. 2(a). Vibrational packing was performed on the test chamber to attain 63% packing fraction. The filled mass of Li_2TiO_3 pebbles in the volume of 578 cc was 1124 gm. The Li_2TiO_3 pebbles have 10% of total

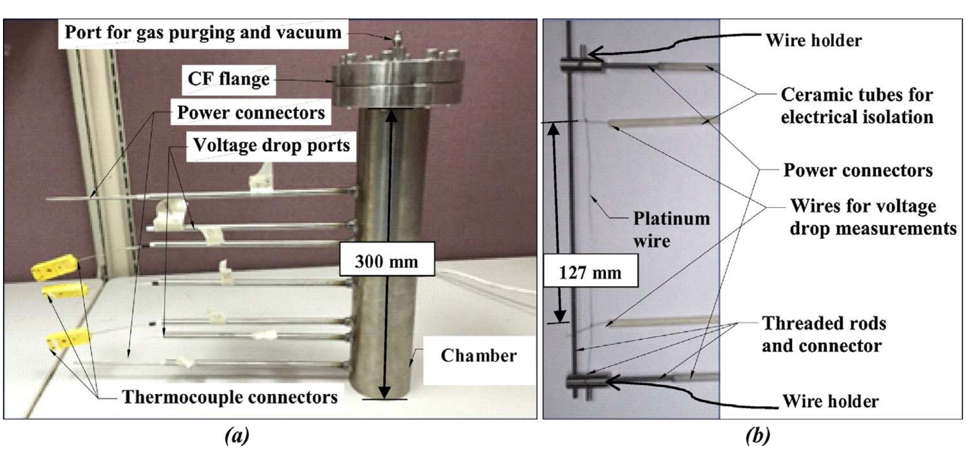

Fig. 1. (a) Transient hot wire experimental setup and (b) Hot wire connections.