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# Experimental measurement of effective thermal conductivity of packed lithium-titanate pebble bed

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ABSTRACT

Lithium titanate is a promising solid breeder material for the fusion reactor blanket. Packed lithium titanate pebble bed is considered for the blanket. The thermal energy; that will be produced in the bed during breeding and the radiated heat from the reactor core absorbed must be removed. So, the experimental thermal property data are important for the blanket design. In past, a significant amount of works were conducted to determine the effective thermal conductivity of packed solid breeder pebble bed, in helium atmosphere, but no flow of gas was considered. With increase in gas flow rate, effective thermal conductivity of pebble bed increases. Particle size and void fraction also affect the thermal properties of the bed significantly. An experimental facility with external heat source was designed and installed. Experiments were carried out with lithium-titanate pebbles of different sizes at variable gas flow rates and at different bed wall temperature. It was observed that effective thermal conductivity of pebble bed is a function of particle Reynolds number and temperature. From the experimental data two correlations have been developed to estimate the effective thermal conductivity of packed lithium-titanate pebble bed for different particle Reynolds number and at different temperatures. The experimental details and results are discussed in this paper.



## 1. Introduction

Lithium titanate ($Li_2TiO_3$) is one of the promising solid breeder materials, considered for the fusion reactors. Since last two decades; worldwide efforts have been dedicated to its R&D [1–12]. The other probable solid breeders are lithium oxide ($Li_2O$), lithium orthosilicate ($Li_4SiO_4$), and lithium-metazirconate ($Li_2ZrO_3$). Spherical $Li_2TiO_3$ pebbles of size 0.4–1.0 mm, with characteristic properties, density; 80–85% of theoretical density (3.42 g cm$^{-3}$), ~7% open and ~ 4% close porosity, 1–6 μm grain size, etc. [1,2] are considered suitable, for use in Test Blanket Module (TBM) of ITER DEMO reactor. Solid breeder materials are required to have good thermal properties along with satisfactory tritium breeding. For the good design of the blanket, the experimental measurement of the effective thermal conductivity of the pebble bed is necessary.

In past, significant amount of studies were conducted by many investigators, to determine the effective thermal conductivity ($k_{eff}$) of lithium ceramics pebble bed. In 1990, Donne and Sordon [3] were the first to measure $k_{eff}$ of solid breeder material. They measured $k_{eff}$ of $Li_4SiO_4$ pebble bed; of pebble size 0.5 mm in the temperature range from 50 to 350 °C under 1 bar stagnant helium atmosphere. In the following year; Sullivan [4] reported their measured $k_{eff}$ values for $Li_2ZrO_3$ pebble bed. They had conducted experiments at 0.1 MPa helium atmosphere in the temperature range of 70–500 °C. Enoeda et al. [5] conducted experiments to measure $k_{eff}$ of $Li_2O$ pebble bed, in 1994. Donne and Sordon [6] repeated their experiments in 1994, to measure $k_{eff}$ of 0.35–0.6 mm $Li_4SiO_4$ pebble bed. Lorenzetto et al. [7] presented experimental results of $k_{eff}$ of $Li_2ZrO_3$ pebble bed in 1995. They conducted experiments over a temperature range of 100–1175 °C. In 1998, Earnshaw et al. [8] measured $k_{eff}$ of 1.2 mm $Li_2ZrO_3$ pebble bed, under helium over a temperature range of 75–1170 °C. In 2000, Donne et al. [9] also measured $k_{eff}$ of $Li_4SiO_4$ pebble bed. In 2001, Enoeda et al. [10] measured $k_{eff}$ of $Li_2TiO_3$, $Li_4SiO_4$, $Li_2ZrO_3$, and $Li_2O$ pebble beds under helium atmosphere and presented correlations based on experimental results. Hatano et al. [11] determined $k_{eff}$ of $Li_2TiO_3$ pebble bed at vacuum to 0.2 MPa helium atmosphere and temperature range from 420 to 775 °C. In 2002, Hoshino et al. [12] reported their study on effective thermal conductivity of single and binary pebble bed of $Li_2TiO_3$ pebbles. In 2005, Tanigawa et al. [13] measured $k_{eff}$ of compressed $Li_2TiO_3$ pebble bed and in 2007; Abou-Sena

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $c_{p,g}$ | heat capacity of gas [J kg$^{-1}$ K$^{-1}$] |
| $D_b$ | column or bed diameter [m] |
| $d_p$ | particle diameter [m] |
| $g$ | acceleration due to gravity [m s$^{-2}$] |
| $G$ | mass velocity of gas [kg m$^{-2}$ s$^{-1}$] |
| $h$ | heat transfer coefficient [W m$^{-2}$ K$^{-1}$] |
| $h$ | heat transfer coefficient [W m$^{-2}$ K$^{-1}$] |
| $k_e^o$ | effective thermal conductivity of the bed at zero gas flow-rate [W m$^{-1}$ K$^{-1}$] |
| $k_{eff}$ | effective thermal conductivity of pebble bed [W m$^{-1}$ K$^{-1}$] |
| $k_{e,r}$ | effective thermal conductivity of pebble bed at radial position $r$ [W m$^{-1}$ K$^{-1}$] |
| $k_{e,z}$ | is the effective thermal conductivity of the bed along axial ($Z$) direction [W m$^{-1}$ K$^{-1}$] [W m$^{-1}$ K$^{-1}$] |
| $k_g$ | thermal conductivity of gas [W m$^{-1}$ K$^{-1}$] |
| $k_s$ | thermal conductivity of solid particle [W m$^{-1}$ K$^{-1}$] |
| $k_e^o$ | thermal conductivity of pebble bed at zero air velocity [W m$^{-1}$ K$^{-1}$] |
| $k_z$ | effective thermal conductivity of pebble bed at axial position $z$ [W m$^{-1}$ K$^{-1}$] |
| $m$ | mass of particles [kg] |
| $r$ | radius [m] |
| $R$ | radius of bed [m] |
| $\mathrm{Re}_p$ | particle Reynolds number ($d_p u \rho_g/\mu$) |
| $T_g$ | temperature of gas [K] |
| $T_{ge}$ | exit gas temperature [K] |
| $T_{gi}$ | inlet gas temperature [K] |
| $T_w$ | bed wall temperature [K] |
| $u$ | air velocity [m s$^{-1}$] |
| $u_o$ | superficial air velocity [m s$^{-1}$] |
| $u_o$ | superficial air velocity [m s$^{-1}$] |
| $u_{mf}$ | minimum fluidization velocity [m s$^{-1}$] fluidization |
| $q$ | heat flow flux [W m$^{-2}$] |
| $z$ | axial bed height [m] |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | void fraction |
| $\varepsilon_{mf}$ | void fraction at minimum fluidization |
| $\varphi_S$ | particle sphericity |
| $\rho_g$ | density of gas [kg m$^{-3}$] |
| $\rho_s$ | density of pebbles [kg m$^{-3}$] |
| $\mu$ | viscosity of gas [kg m$^{-1}$ s$^{-1}$] |

et al. [14] measured $k_{eff}$ of $Li_2TO_3$ pebble bed; also under helium atmosphere.

$Li_2TiO_3$ has low thermal conductivity (~2.5 W m$^{-1}$ K at 500 K), which is reduced further when used in packed pebble bed. This is due to the presence of significant amount of voids and also point-to-point contact among the pebbles. Wall effect in the packed bed plays a significant role for a cylindrical bed with low particle size ($d_f$) to bed diameter ($D_b$) ratio ($d_p/D_b$). ITER presently specifies lithium titanate pebbles of size 0.4–1.0 mm for both Helium Cooled Ceramic Breeder (HCCB) and Lead Lithium alloy Cooled Breeder (LLCCB) type TBM. Both fusion and tritium generation reactions are exothermic. Hence, it is necessary to cool the TBM and it is also important; to enhance the thermal conductivity of $Li_2TiO_3$ pebble bed. It is proposed to apply packed fluidization technique; in which smaller size pebbles (0.2–0.78 mm) are allowed to fluidize in the interstices of larger (3–10 mm) and stationery pebbles, to get the advantages of fluidization. The conventional fluidization need higher gas velocity, which is not desirable in TBM. It was observed that the minimum fluidization velocity of solid particles is lower in packed fluidized bed compared to that in a convectional fluidized bed. Minimum fluidization velocity also decreases with increase in temperature. So, the fine particles may be fluidized at very low gas velocity in the interstices of large pebbles and $k_{eff}$ of the pebble bed may be increased.

All the earlier experiments on $k_{eff}$ of solid breeder pebble bed were conducted under stagnant helium atmosphere. The effect of flow of helium or any other gas on $k_{eff}$ of the pebble bed was not considered. The effect of pebble size on $k_{eff}$ of the pebble bed was also not measured. This paper reports experimentally measured $k_{eff}$ values of packed $Li_2TiO_3$ pebble bed, with different pebble sizes, different air flow-rates and different wall temperatures. Temperature gradients, both in the axial direction (direction of gas flow) and radial direction (perpendicular to the gas flow) were measured, in a 162.74 mm inside diameter column, packed with $Li_2TiO_3$ pebbles. Experiments were conducted with $Li_2TiO_3$ pebbles of five different sizes pebbles viz., 1, 3, 5, 7, and 10 mm. The experimental results were compared with alumina ($Al_2O_3$) pebbles of sizes 1, 3, 5, and 10 mm. The bigger pebbles were selected to find the suitability of packed fluidization technique for enhancement of $k_{eff}$ of pebble bed. The present paper describes experimental results on packed bed. The experimental results on packed-fluidized bed will be described in a separate paper. From these data $k_{eff}$ values, were estimated. Since the bed wall temperature used in the experiments up to 600 °C, radiation effect was neglected and gas convection was accounted in the effective thermal conductivity term.

## 2. Theory and model equations

Yagi and Kunii [15] has suggested that, in pebble bed heat is transferred through the following mechanisms:

(a) Heat transfer through the contact surface of the particles;
(b) radiant heat transfer between surfaces of the particles;
(c) radiant heat transfer between adjacent voids;
(d) heat transfer through the film near the contact surface; and
(e) heat transfer by convection, solid–gas–solid.

Kunii and Smith [16] proposed that particles are surrounded by stagnant fluid. Heat is transfer in, by following mechanisms:

(a) Heat is transfer through the fluid in the void space by conduction and by radiation between adjacent voids (when the voids are assumed to contain a non-absorbed gas);
(b) heat is transferred through the solid phase through the contact surface of the solid particles;
(c) conduction through the stagnant fluid near the contact surface and radiation between surfaces of the solid); and
(d) conduction through the solid phase.

In addition to the above mechanisms, Ranz [17] has stated that in pebble bed heat is also transfer by lateral mixing of gas. The convection is predominant at relatively high gas velocities and radiation is considered at temperature higher than 600 °C. Due to the local variation of voidage, pebble shape; size and distribution, velocity distribution of gas, the heat transfer properties of bed varies locally. This causes problem in accurately measure the thermal conductivity of the bed. Heat transfer in gas–solid packed pebble bed systems was critically reviewed by Barker [18], Zehner and Schlunder [19] discussed about the effective conductivity in packed beds with flowing fluid at medium and high temperatures. Bauer and Schlunder [20] proposed a model to estimate effective thermal conductivity of packed bed under gas flow condition. Balakrishnan and