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Experimental investigation of effective thermal conductivity of packed lithium-titanate pebble bed with external heat source and flow of helium

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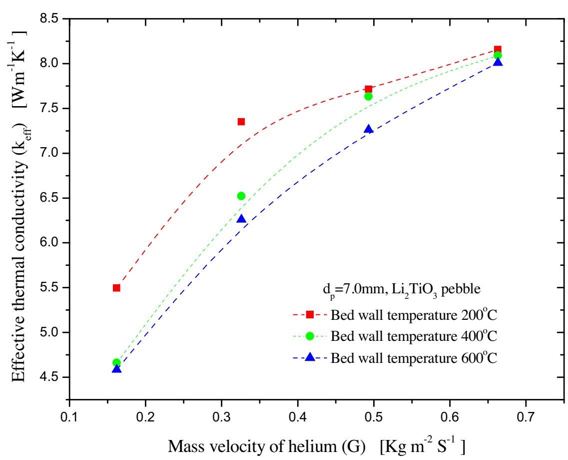
HIGHLIGHTS

- In the present study helium gas was used to determine k_{eff} of Li_2TiO_3 pebble bed.
- Effects of gas flow rate, temperature and pebble size on k_{eff} were investigated.
- It was found that the value of k_{eff} increases by many folds with use of helium.
- Value of k_{eff} dependent on particle Reynold's number and bed temperature.
- Value of k_{eff} of Li_2TiO_3 pebble bed at $0.292\,ms^{-1}$ helium velocity was $10\,Wm^{-2}\,K^{-1}$.

GRAPHICAL ABSTRACT

The following figure shows the effect of mass velocity of air on effective thermal conductivity of packed pebble bed of 7 mm Li_2TiO_3 pebbles.



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ABSTRACT

Packed pebble bed of ceramic solid breeder materials viz. lithium titanate or meta-titanate (Li_2TiO_3), lithium orthosilicate (Li_4SiO_4) etc. is being considered for fusion blankets. During the breeding of tritium, helium will be produced and also it is proposed to flow helium from outside through the bed to extract tritium, as well as to remove thermal energy from the bed. Experimental determination of thermal property data of the pebble bed under helium gas flow is important for the blanket design. Such study of determination of effective thermal conductivity with flowing helium condition was not performed previously. Though, it is known that with an increase in gas flow rate, the effective thermal conductivity of pebble bed increases, it is necessary to conduct experiments to know the exact values and the degree of variation. Model and experimental setup used in our previous study was used to for this present work. Effects of process parameters viz., helium gas flow rate, bed temperature, pebble size etc. on the effective

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thermal conductivity of the bed have been studied. Correlations have been developed from these experimental data to estimate effective thermal conductivity at different particle Reynold's number and bed temperature. It was found that with the use of helium, the effective thermal conductivity of bed increases by many folds. Experimental details and results are discussed in this paper.

Nomenclature

Symbols

A_t	Cross-sectional area of bed [m^2]
$c_{p,g}$	Heat capacity of gas [$J\,kg^{-1}\,K^{-1}$]
d_p	Particle diameter [m]
g	Acceleration due to gravity [$m\,s^{-2}$]
G	Mass velocity of gas [$kg\,m^{-2}\,s^{-1}$]
H	Static bed height [m]
H_f	Fluidized bed height [m]
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 [$W\,m^{-1}\,K^{-1}$]
$k_{h,T}$	Thermal conductivity of helium at ambient temperature [$W\,m^{-1}\,K^{-1}$]
k_s	Thermal conductivity of solid particle [$W\,m^{-1}\,K^{-1}$]
$k_{e,o}$	Thermal conductivity of pebble bed at zero air velocity [$W\,m^{-1}\,K^{-1}$]
m	Mass of particles [kg]
r	Bed radius [m]
Re_p	Particle Reynolds number []
T_a	Temperature of gas [K]
T_b	Bed temperature [K]
$T_{g,i}$	Inlet gas temperature [K]
u_{mf}	Minimum fluidization velocity [$m\,s^{-1}$]
u_s	Superficial air velocity [$m\,s^{-1}$]
q	Heat flow rate [W]
z	Axial bed height [m]

Greek letters

ε	Void fraction [-]
ε_{mf}	Void fraction at minimum fluidization [–]
ϕ_S	Particle sphericity [-]
ρ_g	Density of gas [$kg\,m^{-3}$]
ρ_s	Density of pebbles [$kg\,m^{-3}$]
μ	Viscosity of gas [$kg\,m^{-1}\,s^{-1}$]

1. Introduction

Low thermal conductivity of pebble bed of solid breeder material, viz. lithium titanate, lithium orthosilicate etc. is a key issue to the development to fusion reactor [1,2], since the efficiency to extract heat from blanket will decide the success of DEMO reactor. Various lithium-based compounds viz., lithium oxide (Li_2O), lithium orthosilicate (Li_4SiO_4), lithium zirconate (Li_2ZrO_3), lithium titanate (Li_2TiO_3) etc. have been studied till date as solid breeder blanket materials of DEMO reactors. Among these lithium based ceramics, lithium titanate (Li_2TiO_3) has been studied extensively by many researchers, due to its excellent chemical stability, lower activation energy, comparatively higher thermal conductivity and efficient tritium release [3–5]. Li_2TiO_3 pebbles with varying diameter range were fabricated by various researchers with the help of various techniques. One of such a technique is manufacturing of Li_2TiO_3 pebbles by solid state reaction and spherodization [4,5].

For the efficient design of the blanket, the rate of removal heat from the blanket due to the fusion reaction in should be high [6]. So in order to have a high heat extraction, the effective thermal conductivity of blanket module should be as high as possible. Mandal et al. [6] have reported that due to the wall effect in the packed bed and higher percentage of voids, effective thermal conductivity of bed of lithium titanate pebbles is low. This effective thermal conductivity may be increased with the use of the packed fluidization technique in which the smaller size pebbles (0.2–0.8 μm) are fluidized in the interstices of larger pebbles (of size: 3–10 mm). The packed fluidization decreases the minimum fluidization velocity which is desirable for TBM. In the past, many researchers have studied the fluidization phenomenon to calculate the effective thermal conductivity (k_{eff}) of packed pebble bed. Li et al. [7] measured thermal conductivity of Li_4SiO_4 and Li_2TiO_3 pebble bed with stagnant helium at 3 bar at steady state and unsteady state condition. Mandal et al. [6] determined the effective thermal conductivity of Li_2TiO_3 pebble bed under flowing air condition and studied the effect of temperature, pebble size and mass flow rate of air. Abou-Sena et al. [8] reported the k_{eff} Li_2TiO_3 pebble bed of pebble size 1.7–2.0 mm in the temperature range of 50 °C–500 °C with helium as a cover gas. Similarly, Hatano et al. [9], Donne et al. [10], Earnshaw et al. [11], Lorenzetto et al. [12] and Suvillian et al. [13] determined the effective thermal conductivity of Li_2TiO_3 pebble bed of different pebble sizes at different temperature filled with stationary helium gas.

In all the earlier experiments, k_{eff} of pebble bed of solid breeder pebble bed was conducted under stagnant helium atmosphere. Till date, the effect of the flow of helium gas on k_{eff} of the pebble bed of solid breeder materials viz., Li_2TiO_3, Li_4SiO_4 etc. has not yet been studied. Experimental data on the effect of pebble size, bed wall temperature, mass flow rate on the k_{eff} of the pebble bed of Li_2TiO_3 with flowing helium gas is very important for the effective design of TBM. Experiments were carried out to determine k_{eff} values of packed Li_2TiO_3 pebble bed of different pebble sizes and the effect of helium flow-rates, and bed wall temperatures on the k_{eff} were investigated. 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 of different sizes (0.78–10 mm). The large size pebbles (>1.0 mm) and smaller size pebbles (<1.0 mm, henceforth called particles) were selected to find the suitability of packed fluidization for enhancement of k_{eff} of bed of Li_2TiO_3 pebbles.

2. Models for the determination of k_{eff}

Many models have been developed and reported in literature to determine the effective thermal conductivity of pebble bed. Abou-Sena et al. [8] have listed few such models to determine effective thermal conductivity of pebble bed, these include Schlunder, Zehner, and Bauer model, Shapiro et al. model, Okazaki et al. model etc. They found that experimentally determined effective thermal conductivity values were well fitted with Okazaki et al. model.

Mandal et al. [6] have developed a pseudo-homogenous two-dimensional model for the determination of effective thermal