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Theoretical modeling of the effective thermal conductivity of the binary pebble beds for the CFETR-WCCB blanket

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HIGHLIGHTS

- A modified SZB (M-SZB) model is proposed for estimation of effective thermal conductivity of binary pebble beds with different materials.
- The M-SZB model considers the influence of packing factor, particle size, pressure, temperature, contact area.
- The M-SZB model agrees well with experimental data within a deviation of 20%.
- Calculate the effective thermal conductivity of binary mixed pebble beds by M-SZB model for WCCB.

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ABSTRACT

The effective thermal conductivity (k_{eff}) is an important characteristic parameter for the thermo-hydraulics analysis of the ceramic breeder blanket. However, for the binary pebble beds composed of different particle materials, the experimental data of k_{eff} were very rare in the literature and limited theoretical models were found to be suitable for the accurate prediction. In this study, we have proposed an improved SZB (M-SZB) model to obtain the k_{eff} for the binary pebble beds composed of different particle materials. For the $Li_2TiO_3/Be_{12}Ti$ mixed pebble bed which used in the design of water-cooling ceramic breeder blanket(WCCB) for the China Fusion Engineering Test Reactor (CFETR), the k_{eff} values were calculated by the proposed SZB model and they ranges between 2.0 and 4.0 W/(m·K).

1. Introduction

The development of water-cooling ceramic breeder blanket (WCCB) has been carried out [1] as one of the potential candidates for the breeding blankets of the China Fusion Engineering Test Reactor (CFETR). In the WCCB, the $Li_2TiO_3/Be_{12}Ti$ mixed pebble bed is selected with the Li_2TiO_3 as the primary tritium breeder and $Be_{12}Ti$ as the neutron multiplier. In order to characterize thermal performances of the WCCB, the study of the effective thermal conductivity (k_{eff}) for the pebble bed mixed with Li_2TiO_3 and $Be_{12}Ti$ particles is necessary.

Previous studies have been carried out, either using theoretical models [2–5], or doing experiments [5–9] and numerical simulations [10,11], to obtain the k_{eff} of the unitary pebble bed, which usually focused on the pebble beds with only a single particle material. However, studies on the k_{eff} of binary pebble beds composed of different particle materials are very rare. For example, Ades and Peddicord [10], and Adnani et al. [11] proposed the numerical model for the binary pebble bed, respectively. Both numerical models used two dimensional definite difference method and their results were found to agree well with existing experimental data. However, such numerical models are very complex in math and cannot explicitly explain the dominant factors which impact on the k_{eff}. In another study, Okazaki et al. [12] developed a theoretical model for the binary pebble bed using the volumetric average method. However, it was found to induce large deviation when compared with experimental data from other researchers [13]. Also, Slavin et al. [13] proposed a model to calculate the k_{eff} of binary pebble beds by considering a characteristic parameter for particle roughness. Since most existing experiments didn't measure particle roughness, Slavin's method is quite difficult to validated and compared with existing experimental data. To calculate the k_{eff} of binary pebble beds composed of different particle materials, i.e. the $Li_2TiO_3/Be_{12}Ti$ mixed pebble bed for the WCCB, a theoretical model evolved from Schlünder, Zehner and Bauer' s SZB

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Nomenclature

C_f	particle form factor in SZB model
C_p	specific heat at constant pressure [J/(kg·K)]
d	diameter of particles [m]
d_t, d_l	diameter of tiny particles and large particles, respectively [m]
k_c	ratio of thermal conductivity of the core of the unit cell to k_g in SZB model
k_s	thermal conductivity of solid materials [W/(m·K)]
k_s^*	modified thermal conductivity of solid materials with a gas film outside the particles in M-SZB model [W/(m·K)]
k_g	thermal conductivity of gas at high pressure [W/(m·K)]
k_{eff}	effective thermal conductivity of pebble beds [W/(m·K)]
$k_{\text{eff},t}$	effective thermal conductivity of the tiny pebble beds [W/(m·K)]
k_D	ratio of gaseous conduction in the Knudsen regime to k_g in SZB model
k_R	ratio of thermal conductivity of radiative heat transfer to k_g in SZB model
M_g, M_s	molar mass of gas and solid [kg/mol]
P	Gaseous pressure of pebble beds [Pa]
PF	packing factor of pebble beds, $1-\varepsilon$
Pr	Prandtl number of gas
$\tilde{R}$	ideal gas constant [J/(mol·K)]
T	temperature [K]
V_l	volume fraction of large particles
w	effective thickness of the gas film in M-SZB model

Greek symbols

α	thermal accommodation coefficient
γ	emissivity
ε	porosity of pebble beds
κ	$\kappa = k_s/k_g$
μ	$\mu = M_g/M_s$
σ	radiation constant of the black body [W/m^2/K^4]
ϕ	particle flattening coefficient in SZB model
ρ_K^2	the contact-area fraction

Subscripts

l, t	large particles, tiny particles
s, g	solid, gas

model[3], called the modified SZB model (M-SZB), was proposed in this work.

In this study, the SZB model will be introduced in Section 2. Then, we will talk about the M-SZB model in Section 3. Benchmark and limitations of the M-SZB model will be presented and discussed in Section 4. Calculation results and discussions will be given in Section 5. Finally, we will give the conclusions in Section 6.

2. SZB model

The SZB model [3] was developed based on the unit cell approach and Fig. 1(a) shows the unit cell of a unitary pebble bed. This model uses the deformation factor (B) to represent the shape change of a particle in the unit cell of a pebble bed. The deformation factor and the porosity of pebble beds satisfy the following equation:

$$B = C_f\left[\frac{(1-\varepsilon)}{\varepsilon}\right]^{10/9} D_f \tag{1}$$

where ε is the porosity of the pebble bed, C_f is the particle form factor, and D_f is the size distribution function of the particles. Usually, a C_f = 1.25 is used for the spherical particles and D_f = 1 is used for the mono-sized particles. When particles' sizes are different, D_f is served as a function of the diameters and volume fraction [3].

With the considerations of the conduction of solid particles (k_s), stagnant fluid/gas (k_g), dimensionless conduction through the core of the unit cell (k_c), and dimensionless radiative conductivity between solid surfaces (k_R), the effective conductivity of the pebble beds can be calculated directly by the following equation

$$\frac{k_{\text{eff}}}{k_g} = \left(1-\sqrt{1-\varepsilon}\right)\varepsilon\left[\left(\varepsilon-1+k_D^{-1}\right)^{-1}+k_R\right] + \sqrt{1-\varepsilon}\left[\phi\kappa+(1-\phi)k_c\right] \tag{2}$$

where

$$k_c = \frac{2}{N}\left\{\frac{B(\kappa+k_R-1)}{N^2\kappa k_D}\ln\frac{\kappa+k_R}{B\left[k_D+(1-k_D)(\kappa+k_R)\right]} + \frac{B+1}{2B}\left[\frac{k_R}{k_D}-B\left(1+\frac{1-k_D}{k_D}k_R\right)\right]-\frac{B-1}{Nk_D}\right\} \tag{3}$$

$$N = \frac{1}{k_D}\left(1+\frac{k_R-Bk_D}{\kappa}\right)-B\left(\frac{1}{k_D}-1\right)\left(1+\frac{k_R}{\kappa}\right),$$

$$k_R = \frac{k_r}{k_g} = \frac{4\sigma}{2/\gamma-1}\frac{T^3 d}{k_g} \tag{4}$$

where κ is the ratio of k_s to k_g, k_D is the dimensionless gaseous conduction related to the Knudsen regime, and ϕ is a parameter describing the additional contact conduction through the contiguous particles. According to Ref. [3], ϕ can be given by the following equation:

$$\phi = \frac{23\rho_K^2}{1+22\rho_K^{4/3}}, \quad \rho_K^2 = \left(\frac{d_K}{d}\right)^2 \tag{5}$$

where d and d_K are the diameters of the particles and the contact surface, respectively. Since d_K is a function of many factors, such as irradiation swelling, external mechanical stress and surface state of the material, the contact-area fraction ρ_K^2 can be found through an experimental approach [3]. The SZB model can be applied to predict k_{eff} of the binary pebble beds containing the particles of the same material with different sizes.

3. M-SZB model for the binary pebble beds composed of different particle materials

3.1. Basic derivation of M-SZB model

A numerical method reported in [10] has been used to calculate the k_{eff} of a multi-sized pebble bed. In this study, by combining the basic assumptions in the above numerical method and the SZB model, a new theoretical method is proposed to estimate the k_{eff} of the binary pebble beds composed of different particle materials. Fig. 1(b) illustrates the unit cell of the binary pebble beds. It is assumed that $d_l \gg d_t$ and thus large particles are surrounded by smaller particles [10]. A large numbers of mixed smaller particles can be treated as a "tiny pebble bed" and its effective thermal conductivity ($k_{\text{eff},t}$) can be calculated by the SZB model. In this situation, it seems that the space between large particles is filled with a homogeneous medium. Therefore, the effective thermal conductivity of the binary pebble beds can be calculated by using the heat transfer analysis of the unitary unit cell similar as that used in the SZB model. At the same time, stagnant fluid phase and parallel path of heat flux are also needed to be assumed just as what was done in