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A prediction model for the effective thermal conductivity of mono-sized pebble beds

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HIGHLIGHTS

- One new method to couple the contact area with bed strain is developed.
- The constant coefficient to correlate the effect of gas flow is determined.
- This model is valid for various cases, and its advantages are showed obviously.

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ABSTRACT

A model is presented here to predict the effective thermal conductivity of porous medium packed with mono-sized spherical pebbles, and it is valid when pebbles' size is far less than the characteristic length of porous medium just like the fusion pebble beds. In this model, the influences of parameters such as properties of pebble and gas materials, bed porosity, pebble size, gas flow, contact area, thermal radiation, contact resistance, etc. are all taken into account, and one method to couple the contact areas with bed strains is also developed and implemented preliminarily. Compared with available theoretical models, CFD numerical simulations and experimental data, this model is verified to be successful to forecast the bed effective thermal conductivity in various cases and its advantages are also showed obviously. Especially, the convection in pebble beds is focused on and a constant coefficient *C* to correlate the effect of gas flow is determined for the fully developed region of beds by numerical simulation, which is close to some experimental data.

1. Introduction

The porous pebble beds have been determined as the promising form of tritium breeders and neutron multipliers in fusion reactors due to their advantages such as small inside thermal gradients under high heat flux, no magnetohydrodynamics (MHD) effect, convenient extraction of tritium, etc. For the thermal-hydraulic and thermo-mechanical design of fusion solid blankets, the bed effective thermal conductivity k_{eff} is a key design parameter and must be known. Since experimental measurements are expensive and need to take a long time, the theoretical calculations appear more necessary and important, especially for the current and future fusion development projects of China such as CFETR (Chinese Fusion Engineering Test Reactor) [1] since such relevant studies are rare in China.

The bed effective thermal conductivity is influenced by many parameters such as thermal conductivities of pebbles and filling gas, bed packing factor, contact areas between pebbles, thermal radiation, gas flow, pebble size, contact resistance, etc. As the parameters that have significant impact [2–4], thermal conductivities of materials and bed packing factor were usually considered in almost all of previous theoretical calculation models [5–13]. Nevertheless, most of models are still incomplete and only conditionally valid. For example, most of models neglected the effect of gas flow [6–13], and some even ignored the contact areas, thermal radiation or pebble size [5,10–13]. However, it is noted that the effect of contact areas is significant for pebble beds with high ratio of solid to gas conductivity k_s/k_f [14,15], radiation is important at elevated temperatures (>1000 K) [16,17] and the effect of gas flow will become significant when gas velocity is high enough (~0.1 m/s)

Abbreviations: CC, body centered cubic; BCP, body centered prismatic; BUC, basic unit cell of pebble bed; CFETR, Chinese Fusion Engineering Test Reactor; DEM, discrete element method; FCC, face centered cubic; MUC, minimum unit cell of pebble bed; PF, packing factor; SC, simple cubic; SZB, Schlünder–Zehner–Bauer model.

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Nomenclature

A	area, m^2
A_c	contact area, m^2
A_{cros}	conduction area, m^2
A_{cros}^B	sectional area of the block, m^2
A_f	cross section area of flow, m^2
A_{rad}	heat transfer area for radiation, m^2
C	parameter
$c_{p,f}$	heat capacity of gas, J/(kg K)
d_p	pebble diameter, m
E_b	emissive power of black body, $W\,m^{-2}$
e	emissivity
f_k	dimensionless non-isothermal correction factor
G_m	mass flux, $kg\,m^{-2}\,s^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_{cond}^{bed}	bed effective thermal conductivity due to conduction, $W\,m^{-1}\,K^{-1}$
k_{conv}^{bed}	bed effective thermal conductivity due to convection, $W\,m^{-1}\,K^{-1}$
k_e	equivalent thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_{eff}	bed effective thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_f	thermal conductivity of gas, $W\,m^{-1}\,K^{-1}$
$k_{rad,L}^{bed}$	bed long-range effective thermal conductivity due to radiation, $W\,m^{-1}\,K^{-1}$
$k_{rad,S}^{bed}$	bed short-range effective thermal conductivity due to radiation, $W\,m^{-1}\,K^{-1}$
k_{rad}^{L}	long-range radiative conductivity of two non-contact hemispheres, $W\,m^{-1}\,K^{-1}$
k_{rad}^{S}	short-range radiative conductivity of two contacted hemispheres, $W\,m^{-1}\,K^{-1}$
k_s	thermal conductivity of solid, $W\,m^{-1}\,K^{-1}$
L	characteristic length of pebble bed, m
L_r	conduction thickness, m
l	dimensionless length of basic unit cell in x direction
l_r	non-dimensional distance
m	dimensionless length of basic unit cell in y direction
n	dimensionless length of basic unit cell in z direction
N_C	coordination number
$\overline{N_C}$	average coordination number
$\tilde{n}$	average coordination flux number
$\tilde{n}_{long}$	long-range coordination flux number
$\tilde{p}$	pebble porosity
Pr	Prandtl number
Q	heat transfer rate, W
Q_{conv}	conductive heat transfer rate, W
Q_{rad}	radiative heat transfer rate, W
q_m	mass flow rate, $kg\,s^{-1}$
R	pebble radius, m
R_0	initial radius, m
R_c	inner solid resistance, $K\,W^{-1}$
R_{cond}	total conduction resistance, $K\,W^{-1}$
R_{cont}	contact resistance, $K\,W^{-1}$
Re_p	particle Reynolds number
R_{in}	resistance through the inner region, $K\,W^{-1}$
R_{out}	resistance through the outer region, $K\,W^{-1}$
R_t	thermal resistance, $K\,W^{-1}$
r_0	radius of contact area, m
T	temperature, K
$\bar{T}$	mean surface temperature of pebbles
$X_{1,2}$	radiation view factor

Greek symbols

β	ratio, $\beta = 1 - k_f/k_s$
Δr	radial deformation, m
ΔT	temperature difference, K
∇T	temperature gradient, $K\,m^{-1}$
δ	thickness, m
ε	bed porosity
ε_r	radial strain, %
ε	volumetric inelastic strain, %
ζ	correction factor
μ	gas viscosity, kg/(m s)
σ	Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\,Wm^{-2}\,K^{-4}$
$\emptyset_c$	contact angle
$\overline{\emptyset_c}$	average contact angle
φ	angle

[5,18]. Besides, the effective thermal conductivity of a mono-sized bed was also reported to depend on the size of pebbles, even for small sizes also [5,7–9].

In addition, many models did not give the methods to calculate the contact areas but generally assume them to be some specific values when predicting k_{eff} [5–7,10–12], while these calculation methods are necessary since the contact areas are unobtainable in practice.

In this study, we dedicate to establish a calculation model for the single size pebble beds where all above parameters will be considered so that it can be used under more complicated conditions. Meanwhile, based on the fact that the bed strains can be measured by experiments we will develop a new method to calculate the contact areas with bed strains. Besides, our study will also focus on the effect of gas flow in pebble beds due to its importance and complexity.

2. Bed effective thermal conductivity

There are three heat transfer mechanisms, namely conduction, convection and radiation in pebble beds. Accordingly, the bed effective thermal conductivity consists of three components:

$$k_{eff} = k_{cond}^{bed} + k_{conv}^{bed} + k_{rad}^{bed} \quad (1)$$

where k_{cond}^{bed}, k_{conv}^{bed} and k_{rad}^{bed} are the bed effective thermal conductivity due to conduction, convection and radiation, respectively.

Based on the Fourier's law and thermal–electrical analogy principle, the equivalent thermal conductivity of each component can be finally derived as:

$$k_e = \frac{\delta}{AR_t} = \frac{Q \cdot \delta}{A\Delta T} \quad (2)$$

where Q is the heat transfer rate, W; ΔT is the temperature difference, R_t is the equivalent thermal resistance, and δ and A are the thickness and sectional area of the considered object, respectively.

3. Porous structure

The porous structure of pebble beds significantly influences k_{eff}. It is noted that the porous structure can be characterized explicitly with bed porosity $\in$ (void fraction), the coordination number N_C (the number of spheres in contact with the sphere under consideration) and the contact angle Φ_c (the angle between the line connecting the center points of two contacted pebbles and the line perpendicular to the direction of the heat flux) [19].