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An improved prediction model for the effective thermal conductivity of compact pebble bed reactors

Ersheng You, Ximing Sun, Fubing Chen, Lei Shi*, Zuoyi Zhang

Institute of Nuclear and New Energy Technology of Tsinghua University, Beijing 100084, China
Collaborative Innovation Center of Advanced Nuclear Energy Technology, Beijing 100084, China
Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Beijing 100084, China

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ABSTRACT

The effective thermal conductivity is a lumped parameter, which determines heat transfer processes in pebble bed reactors, especially for the decay heat removal after shutdown. Generally, it is calculated by the ZBS model, where the contact area fraction φ is an empirical value for the description of the contact conduction, and the Argo & Smith formula is used to consider the radiation effect. However, the model underestimates the radiation contribution in high temperature. On the other hand, the influence of packing fractions is not included in the model, which affects both the contact conduction and the radiation effect. Therefore, an improved ZBS model was proposed in the paper with the refinements in these two aspects. The elastic deformation theory and the interpolation of three typical structured packing were introduced in the improved model, to calculate the contact conduction of random packed beds with the consideration of packing fractions. At the same time, the Robold model was employed in the improved model, in replacement of the simple formula used in the old ZBS model, by the comparison of several radiation correlations. It was shown that the Robold model could increase the radiation exchange factor at the temperature more than 1000 °C, which is attribute to improve the prediction in high temperature. With the validation by SANA and HTO experiments, it was indicated that the improved model is suitable for the conceptual design and analysis of compact pebble bed reactors with mono-sized spherical fuel elements, where the maximum temperature is possibly close to 1600 °C.

1. Introduction

The modular high temperature gas-cooled reactor (HTGR) has been considered as a candidate of advanced nuclear power systems, with inherent safety features and high efficiency of energy utilization. It is designed to dissipate the decay heat by natural heat transport mechanisms, including thermal conduction and radiation, to avoid the possibility of core meltdown under any accident. All the time, lots of analytical and experimental studies have been conducted for the development of pebble bed HTGRs (Achenbach, 1995; Gao and Shi, 2002; Rousseau and Van Staden, 2008; Zhang et al., 2016). In December 2000, the 10 MW test module (HTR-10), designed and constructed by Tsinghua University, reached the first criticality. Afterwards, the demonstration HTR-PM project (Zhang et al., 2016) located in Shidao Bay, Shandong province, was launched to prove the engineering feasibility and economy. It consists of two pebble bed reactor modules, where massive fuel pebbles with the diameter of 60 mm are employed. The ceramic coated TRISO particles are embedded in the center, to retain radioactive fission products without damage under 1620 °C.

For the sake of the reliable heat removal in the core, a thorough understanding of heat transfer mechanisms in the packed bed is essential to ensure the maximum fuel temperature below the limiting value, especially in the loss of forced cooling accidents. It is considered as an important design basis accident for pebble bed HTGRs, where the effective thermal conductivity plays a dominant role in the removal of decay heat. Regardless of the complex processes in the packed bed, as shown in Fig. 1, the parameter is usually derived by lumping all the relevant factors into a representative value.

There are two kinds of methods to determine the lumped value. One is deterministic method that the porous medium is assumed with a specific geometry configuration, and the other is statistical method that the random pebble bed is built on the basis of discrete element methods. ZS model, proposed by Zehner and Schlünder in 1970 (Zehner and Schlünder, 1970), is a typical deterministic method that a cylindrical unit cell is established to analyze the heat transfer between two spheres. However, the hypotheses of point contact and no thermal radiation make the model hardly used in the cases of high temperature and high solid to fluid thermal conductivity ratio. Then, Bauer and

* Corresponding author.
E-mail address: yes13@mails.tsinghua.edu.cn (L. Shi).

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Nomenclature

B	empirical deformation parameter
B_r	radiation transmission number
D_p	pebble diameter, m
E	elastic modulus, Pa
F_E	radiation exchange factor
k_{eff}	effective thermal conductivity, W/(m·K)
l	molecular mean free path, m
N	average contact number
N_a	number of spheres per unit area
N_l	number of spheres per unit length
P	contact pressure, Pa
R_c	radius of contact area, m
R_p	radius of pebble, m
S_F	geometric factor of packing
T	temperature, K
ε	porosity of packed beds
ε_r	surface emissivity
κ_{eff}	dimensionless effective thermal conductivity
κ_{SF}	relative thermal conductivity for the specific process
κ_G	gas conduction ratio in Knudsen regime
κ_r	radiative conduction ratio
κ_s	solid conduction ratio
Λ_s	dimensionless solid conductivity
μ	Poisson ratio
σ	Stephan-Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)
φ	contact area fraction

Schlünder improved ZS model by considering the factors of Smoluchowski effect, area contact, and thermal radiation, thus developed the well-known ZBS model (Bauer and Schluender, 1978a,b). It is widely used in the prediction of effective thermal conductivity for pebble bed HTGRs. With the review of most correlations in the former studies, Antwerpen (Van Antwerpen et al., 2010, 2012) emphasized the importance of the packing structure, and defined two additional parameter, namely the coordination number and contact angle, which are useful to analyze the heat transport phenomena in pebble beds. Furthermore, a multi-sphere unit cell model (Van Antwerpen et al., 2012) was proposed to calculate the effective thermal conductivity in the near-wall region, where the packing structure and heat transfer mechanisms are considered to be different with the bulk region.

Though a surface fraction parameter φ is introduced in the ZBS model, no corresponding formula is given to calculate the contact area. On the other hand, it seems no enough accuracy at high temperature, for the underestimation of radiation contribution. Therefore, an improved ZBS model was developed in the paper, where the Hertz elastic deformation theory was applied to analyze the contact conduction, and the Robold model was adopted to calculate the radiation conduction. Except for the parameters of temperature, pebble diameter, solid and gas thermal conductivity considered in the ZBS model, the influences of packing factor and contact area were also taken into account in the improved model. The DEM results and experimental data derived from the SANA and HTO tests were used to validate the improved model. It indicates that the model is applicable to predict the effective thermal conductivity for the conceptual design of various novel compact pebble bed reactors, with the abilities for flexible design parameters and high outlet temperature up to 1000 °C.

2. Improved ZBS model

ZBS model (Bauer and Schluender, 1978a) is developed based on the cylindrical unit cell, shown in Fig. 2. It is divided into two separate parts through the dashed line, called the inner cylinder region and the outer annular region. The outer region is saturated with gas phase, while the inner region consists of both the solid and gas phases. It is supposed that the heat transfer through these two regions is in parallel. Hence, the total value is the sum of gas conduction and radiation in the outer annulus and the complex heat transfer processes in the inner cylinder. In the meantime, the inner cylinder consists of the contacting zone and the non-contacting zone, according to the dimension of contact area. Therefore, the effective thermal conductivity calculated by the ZBS model is expressed in Eq. (1), where the distribution coefficient in the outer region is $1-\sqrt{1-\varepsilon}$ and the distribution coefficient in the inner region is $\sqrt{1-\varepsilon}$.

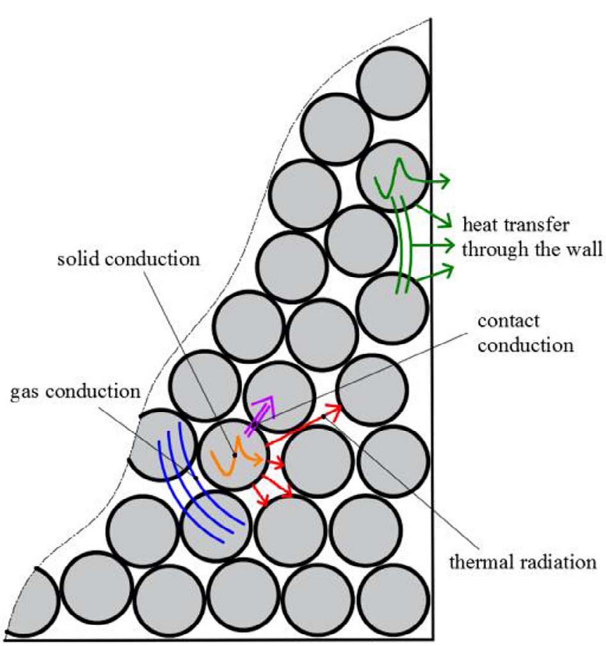

Fig. 1. Heat transfer processes in the pebble bed.

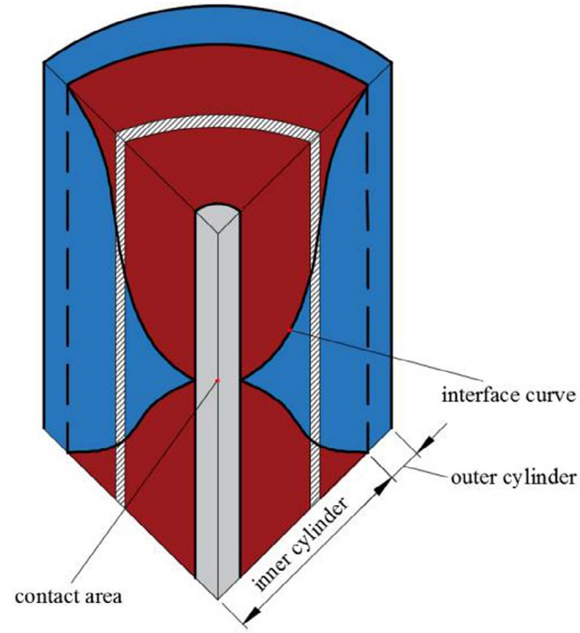

Fig. 2. Cylindrical unit cell in the ZBS model.