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Influence of gas pressure on the effective thermal conductivity of ceramic breeder pebble beds

Weijing Dai [a], Simone Pupeschi [b], Dorian Hanaor [a,c], Yixiang Gan [a,*]

[a] School of Civil Engineering, The University of Sydney, Sydney, Australia
[b] Institute for Applied Materials, Karlsruhe Institute of Technology (KIT), Germany
[c] Institute for Materials Science and Technologies, Technical University of Berlin, Germany

HIGHLIGHTS

- This study explicitly demonstrates the influence of the gas pressure on the effective thermal conductivity of pebble beds.
- The gas pressure influence is shown to correlated to the pebble size.
- The effective thermal conductivity is linked to thermal-mechanical properties of pebbles and packing structure.

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ABSTRACT

Lithium ceramics have been considered as tritium breeder materials in many proposed designs of fusion breeding blankets. Heat generated in breeder pebble beds due to nuclear breeding reaction must be removed by means of actively cooled plates while generated tritiums is recovered by purge gas slowly flowing through beds. Therefore, the effective thermal conductivity of pebble beds that is one of the governing parameters determining heat transport phenomenon needs to be addressed with respect to mechanical status of beds and purge gas pressure. In this study, a numerical framework combining finite element simulation and a semi-empirical correlation of gas gap conduction is proposed to predict the effective thermal conductivity. The purge gas pressure is found to vary the effective thermal conductivity, in particular with the presence of various sized gaps in pebble beds. Random packing of pebble beds is taken into account by an approximated correlation considering the packing factor and coordination number of pebble beds. The model prediction is compared with experimental observation from different sources showing a quantitative agreement with the measurement.

1. Introduction

The lithium orthosilicate, Li_4SiO_4, is one of the most widely investigated lithium ceramic materials in the design of the tritium breeding blanket [1–9]. To maintain the tritium breeding efficiency and reduce the occurrences of mechanical failure including crushing, creeping and swelling, the material form is chosen to be pebble beds instead of directly using sintering blocks [10]. The lithium breeder beds consist of solid phase (nearly spherical-shaped solid particles) and a gas phase (helium) that fills the voids between pebbles. Although the pebble bed has better mechanical stability than sintering blocks, the effective thermal conductivity of the pebble beds is considerably lower than the intrinsic thermal conductivity of Li_4SiO_4 due to the discrete nature of the structure and the existence of the gaseous phase of low thermal conductivity. Therefore, an adequate blanket design is crucial to remove the heat generated inside the pebble bed to guarantee the optimal bed performance for the tritium breeding and extraction. For the design of the cooling system, the effective thermal conductivity of the pebble bed is of primary importance. Many studies have investigated this property experimentally and theoretically [1–3,11]. In general, the effective thermal conductivity of the Li_4SiO_4 pebble beds in different measurement conditions falls into the range around 0.75–1.2 W/mK that is about 4 times lower than thermal conductivity of bulk Li_4SiO_4. Not only the intrinsic properties of the constituent phases of the pebble beds but also other parameter such as the gas pressure, the pebble size, the packing structure, the external loading and other controllable parameters can affect the effective thermal conductivity [1,12].

* Corresponding author.
E-mail address: yixiang.gan@sydney.edu.au (Y. Gan).

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For the Li_4SiO_4 pebble beds, the thermal conductivity ratio between the solid and the gas phase is small. As a result, it is found experimentally that the increase of the contact area introduced by the external loading contributed little to the thermal transport [6,12,13]. While varying the gas pressure is proved to alter the effective thermal conductivity of the pebble beds because the vacancies in the pebble beds are small enough to trigger the Smoluschowski effect in the gas phase [1]. However, only has a few theoretical models considered this gas pressure dependency behaviour [14–17], and such models did not consider explicitly the gas gap conduction at the scale of individual pebbles. To contribute the complete picture between experimental observation and the theoretical explanation, a numerical framework is put forward in this work to illustrate the gas pressure dependency of the effective thermal conductivity of the Li_4SiO_4 pebble beds. Recent work measured a gas pressure drop inside the pebble bed [5], which implies an influence of a non-uniform gas pressure distribution inside the beds on the overall bed performance. During operation cycles, the actual gas pressure inside the bed may differ from the designed value, resulting in a non-uniform distribution of effective thermal conductivity. Such inhomogeneous distribution may cause local heat accumulation inside pebble beds. Design and operation of tritium breeding pebble beds should consider the variation of gas pressure.

This numerical framework is designed to simulate thermal transport processes in the assemblies of individual contact units and then predict the overall thermal conductivity of pebble beds consisting of poly-disperse particles. The relation between the gas pressure effect and particle size is explored. The model prediction shows a quantitative agreement with experimental measurements of the ceramic pebble beds, in particular the gas pressure dependent behaviour.

2. Numerical framework

This numerical framework mainly consists of two parts, the finite element simulation of a representative unit and the homogenisation to assemble the units to predict the effective thermal conductivity. Since this framework is mainly focus on investigating the relation between the gas pressure and the effective thermal conductivity, a model to describe the behaviour of gas heat transfer regarding to the change of gas pressure is prerequisite.

2.1. Gas heat transfer model

In the breeder pebble beds, gases can be recognised as stagnant bulk materials because the purge speed of gases inside the beds is small enough to consider the gases as static. In practise, the thermal conductivity of a gas having a viscosity of μ can be predicted by the modified Eucken equation as

$$k_{Eu} = \frac{9\gamma - 5}{4} * \frac{C_V}{\mu} \tag{1}$$

where $\gamma = \frac{C_P}{C_V}$, is the adiabatic gas constant. C_P and C_V are specific heat at constant gas pressure and constant volume respectively [18].

However, Eq. (1) is applicable when the characteristic length of the space occupied by the gas is much larger than the mean free path of the gas molecules. When the mean free path of the gas molecules is comparable to the characteristic length of the space, the gas thermal conductivity is reduced and the Eucken equation is no longer valid. This phenomenon is called Smoluschowski effect. To quantitatively describe the Smoluschowski effect, the mean free path of the gas molecules needs to be calculated first. As the viscosity of gases is able to be measured in labs and given by an empirical function as [19]

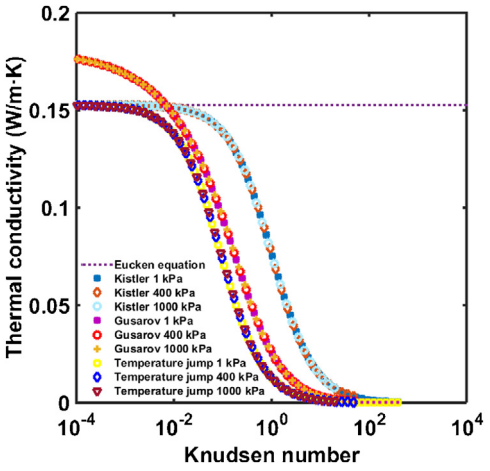

Fig. 1. Helium thermal conductivity predicted by the Gusarov's model, the temperature jump model and the Kistler's model.

$$\mu_{He} = 1.865 * 10^{-5} * \left(\frac{T}{273.16}\right)^{0.7} \tag{2}$$

and according to the kinetic theory, the mean free path l can be calculated by

$$l = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2M}} \tag{3}$$

where P is the pressure of the gas, T is the temperature of the gas, M is the molar mass of the gas and R is the gas constant. The Knudsen number $Kn = l/d$, defined as the mean free path l of the gas molecules over the characteristic length d of the space filled by the gas, is introduced to evaluate the significance of the Smoluschowski effect. A model derived by A.V. Gusarov [18] based on a two parallel plates geometry is applied to explain the dependency of heat transfer coefficient h upon the Kn. When the d is approaching zero (i.e., $Kn \gg 100$), the heat transfer coefficient is reaching the free molecular limit h_0, defined as

$$h_0 = \frac{1}{4}\frac{\gamma+1}{\gamma-1}P\left(\frac{2R}{\pi MT}\right)^{\frac{1}{2}} \tag{4}$$

When Kn decreases, the h follows

$$h = \frac{h_0}{2}\left(\frac{1}{1+1/(\chi * Kn)} + \frac{1}{\left(1+\sqrt{1/\chi * Kn}\right)^2}\right) \tag{5}$$

in which $\chi = \frac{2\sqrt{\pi}}{3}\frac{9\gamma-5}{\gamma+1}$.

The thermal conductivity of helium of 293 K at different gas pressure predicted by different models are compared in Fig. 1, including the temperature jump model and the Kistler model [20]. The Kistler model has the simplest form, $k_K = \frac{k_{Eu}}{1+Kn}$ The temperature jump model adopts a similar form, $k_{TJ} = \frac{k_{Eu}}{1+j/d}$ in which jump distance j is proportional to mean free path l and depends on gas type. Although the Knudsen number Kn is missing in the equation, j/d can be considered to be proportional to Kn. The apparent thermal conductivity ($k_{apparent} = h^* d$) that is converted from the heat conductance coefficient directly obtained from the Gusarov model is used in the plot. All the models show the S shape of the helium thermal conductivity when the Knudsen number is varying. It can be seen from Fig. 1 that the Knudsen number is the essential parameter determining the thermal conductivity of gases, combing the