Theoretical Calculation and Analysis Modelling for the Effective Thermal Conductivity of Lithium Metatitanate Pebble Bed

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COMSOL CONFERENCE INDIA 2012

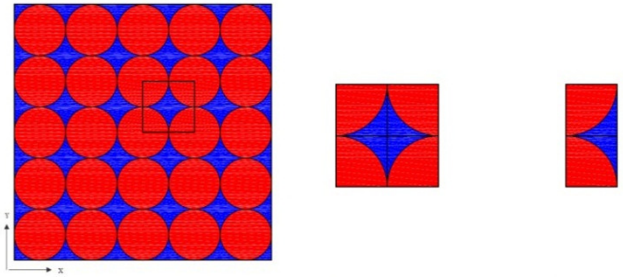
Excerpt from the Proceedings of the 2012 COMSOL Conference in Bangalore

Contents

Introduction

- Lithium based ceramics have been recognized as promising tritium breeding materials for the Fusion reactors.
- In many fusion reactor blankets, as a lithium ceramic material, Lithium metatitante (Li_2TiO_3) will be adopted in form of packed pebble beds (the diameter range of pebbles is form 0.5 mm to 1.5 mm) for tritium breeding and helium as purge gas, to extract generated tritium from the breeder zones.
- Heat is generated in packed pebble bed during interaction between Li_2TiO_3 pebbles and energetic neutrons generated from fusion reaction.
- To understand the temperature profile and heat extraction processes inside the pebble bed, the ETC is an important design parameter for thermo-mechanical design of fusion reactor blankets.
- In this work, the ETC of Li_2TiO_3 pebble bed is estimated by theoretical calculations and modelling analysis.
- The modelling analysis has been carried out using COMSOL 4.3 as numerical tool.

ETC of 2D Li_2TiO_3 pebble bed

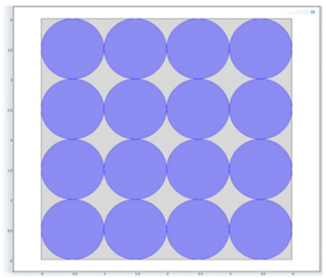


(a) 2D pebble bed (b) Unit cell (c) Half unit cell

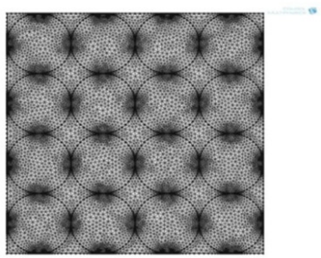
2D array of pebble bed.
Red colour is Li_2TiO_3 pebbles and blue colour is Helium gas.
Packing fraction is 78.5 %.

By using thermal-electrical analogy and heat conduction equation for half of unit cell,
Theoretically ETC for 2D pebble bed can be expressed as,

$$kx = -\frac{kg}{\beta} * \left(\frac{\pi}{2} + \left(\frac{2}{-1+\beta}\right)\sqrt{\frac{-1+\beta}{-1-\beta}}\,\mathrm{arctg}\sqrt{\frac{-1-\beta}{-1+\beta}}\right)$$



2D FEA model
4X4 array of Li_2TiO_3 pebbles with helium gas, The diameter of each pebble is 1 mm.

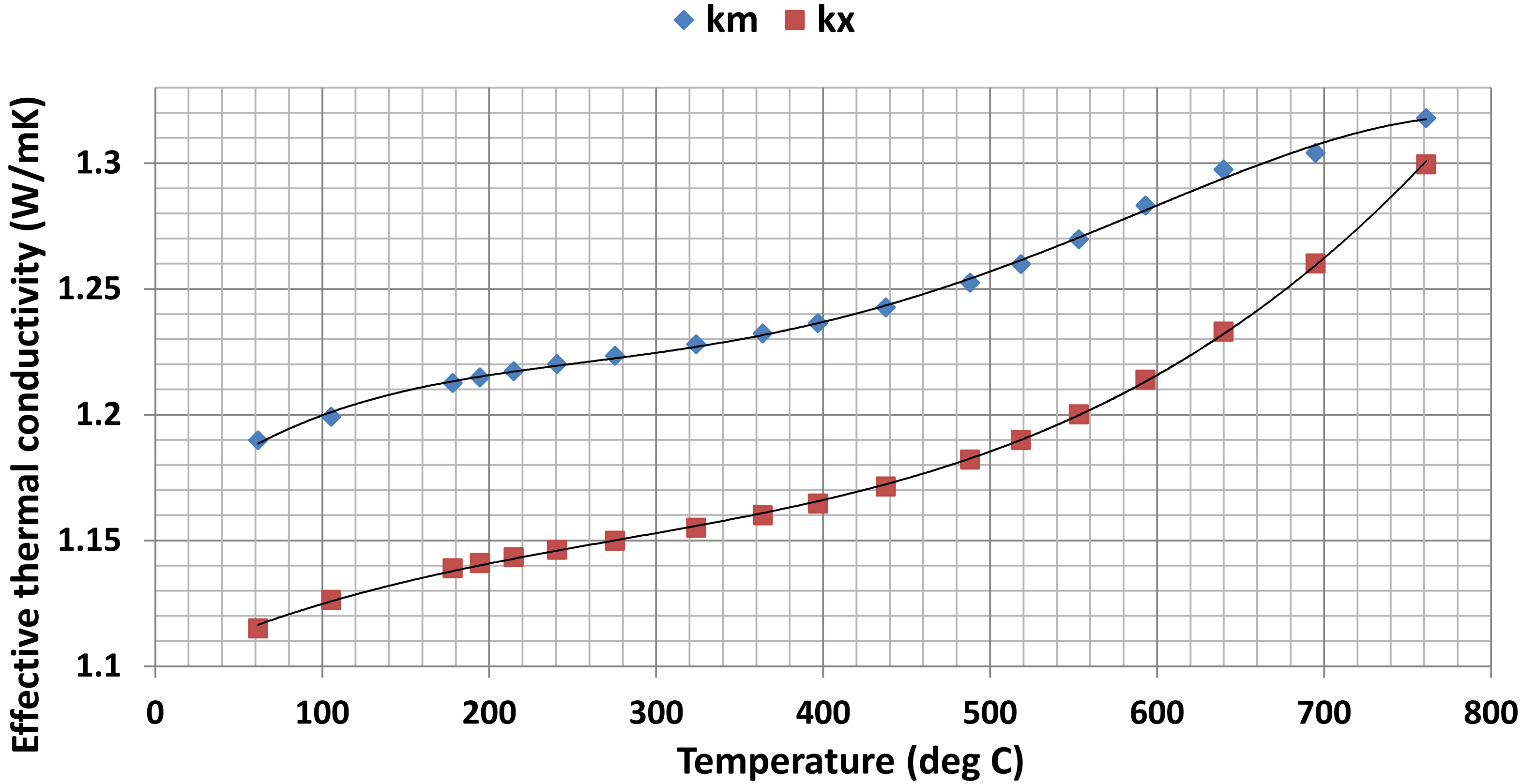


Meshed model
Triangular mesh used,
Maximum element size is 0.12 mm
Minimum element size is 0.00045 mm

Boundary conditions
- Top side is subjected to heat flux of 7000 W/m^2.
- Side walls are thermally insulated.
- Bottom side is convective cooled.

Equation used:
The heat transfer is governed by steady state heat transfer equation,
$q = -k \nabla T$

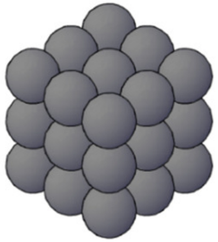
Comparisons of theoretical kx and modelling km results for 2D pebble bed



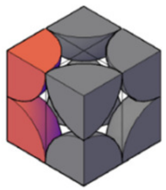
- Both modelling km and theoretical kx increases with temperature increases.
- As temperature increases both km and kx results come closer.
- The relative error is 4.9 %, while considering the km as true value.

ETC for 3D Li_2TiO_3 pebble bed

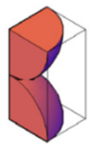
(i) Mono-sized pebble bed



(a) 3D distribution



(b) Unit cell

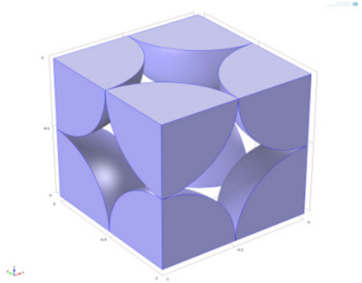


(c) Quarter unit cell

Simple cubic arrangement of pebble bed with helium gas in voids between pebbles,
Packing fraction is 52.33%.

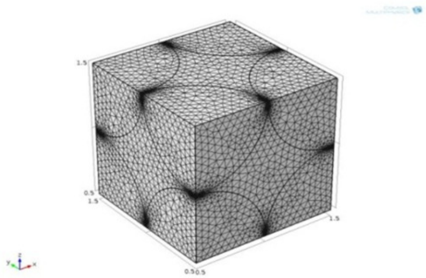
Using thermal-electrical analogy and assuming that heat flows through the pebbles and middle helium gas in parallel for quarter of unit cell, the theoretical ETC for mono-sized pebble bed can be expressed as,

$$ku = \left(1-\frac{\pi}{4}\right) * kg + \left(\frac{\pi * kg}{2 * \beta}\right) * \left(\frac{1}{\beta} * \ln\left(\frac{1}{1-\beta}\right) - 1\right)$$



3D FEA model

Model consists of Li_2TiO_3 pebbles in simple cubic arrangement and helium gas in voids,
1 mm diameter pebbles.



Meshed model

Tetrahedral mesh used,
Maximum element size is 0.1 mm
Minimum element size is 0.018mm

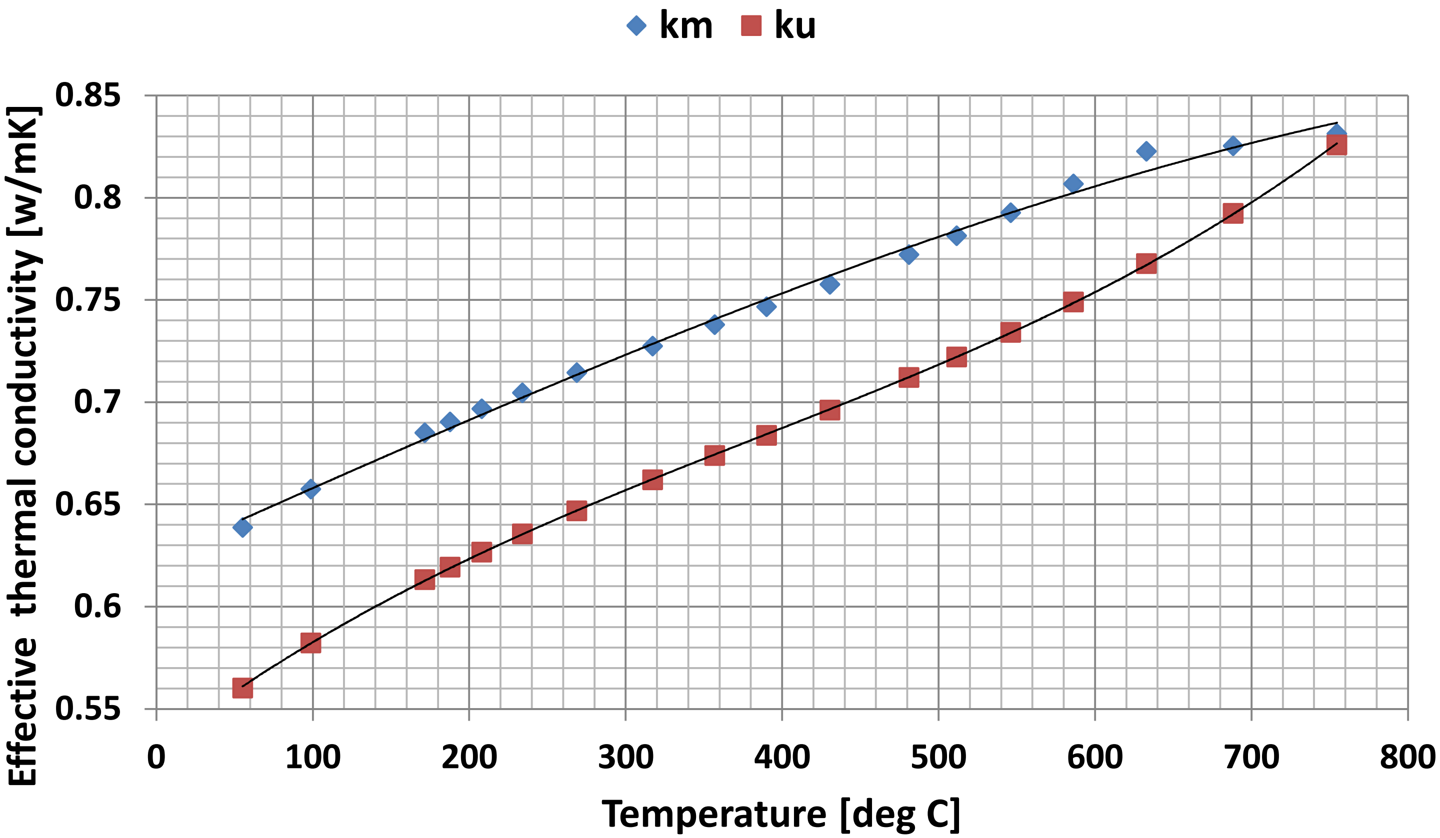
Boundary conditions

- Heat flux of 7000 W/m^2 is applied on top face.
- All four sides are thermally insulated.
- The bottom face is convective cooled,

Equation used:

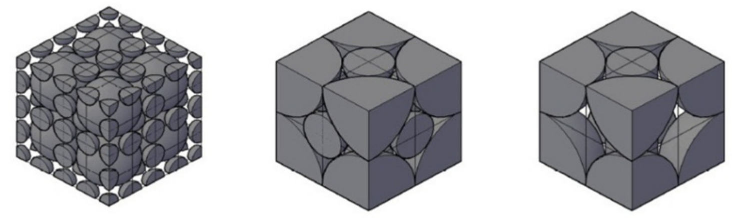
The heat transfer is governed by steady state heat transfer equation,
$q = -k \nabla T$

Comparisons of theoretical ku and modelling km results for mono-sized pebble bed



- Both modelling km and theoretical ku are increasing function of temperature.
- The results of both km and ku are get closer as temperature increases.
- The relative error is 7.85 % estimated, while considering km to be true.

(ii) Binary-sized pebble bed

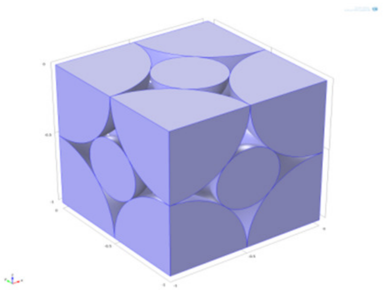


(a) 3D distribution (b) Unit cell (c) Simplified model

3D distribution of binary-sized pebble bed,
Pebble bed consists of 8 large size Li_2TiO_3 pebbles and 32 small size Li_2TiO_3 pebbles,
The diameter ratio is 0.4,
Packing fraction of unit cell is 65.76 % and 64.93 % for simplified model.

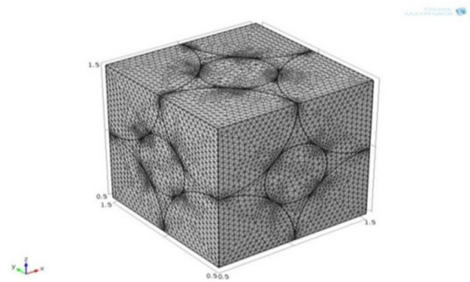
The integral method for binary-sized bed is complex, so for theoretical calculation, a simplified model is used,
By using thermal-electrical analogy approximate ETC for simplified model can be expressed as,

$$kb = \left(\frac{\pi}{4} * kc\right) + \left(\frac{\pi}{4} * (\sqrt{2}-1)^2 * kp\right) + \left(\left(1 - \left(\frac{\pi}{4} + \left(\frac{\pi}{4} * (\sqrt{2}-1)^2\right)\right)\right) * kg\right)$$



3D FEA model

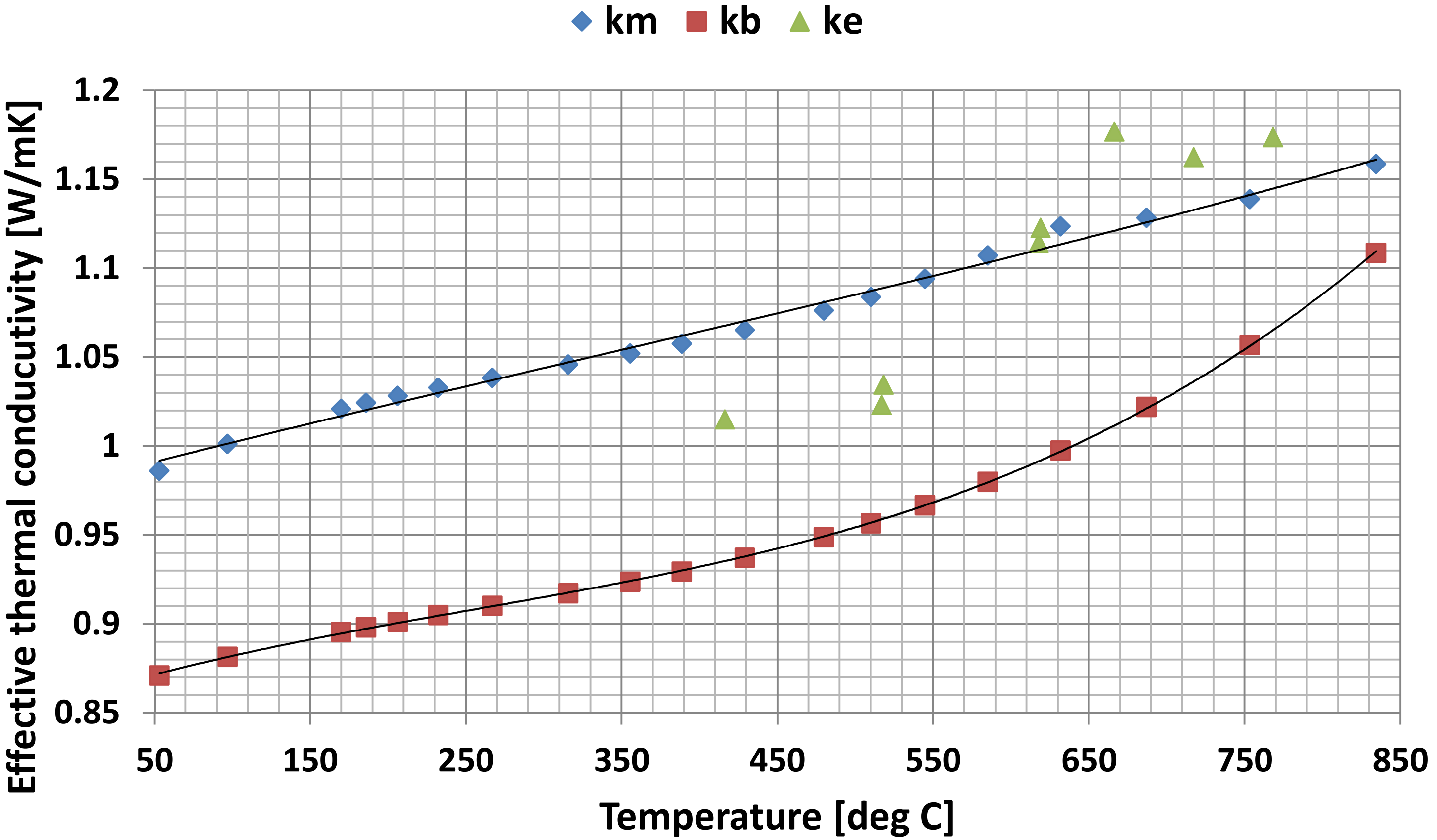
Model consists of large Li_2TiO_3 pebbles in simple cubic arrangement and small Li_2TiO_3 pebbles in between them, helium gas in voids,
The diameter of large size pebble is 1 mm and 0.4 mm for small size pebble.



Meshed model

Tetrahedral mesh used,
Maximum element size is 0.04mm,
Minimum element size is 0.018mm,
The same boundary conditions are used.
The heat transfer is governed by steady state heat transfer equation.

Comparisons of theoretical kb, modelling km and experimental ke results



- The experimental ke results is estimated by hot wire technique for 1.91 mm diameter pebble bed with 60 % packing fraction is used for comparisons.
- Both experimental ke and modelling km increases with temperature increases.
- The approximate theoretical kb result is also increasing function of temperature but the value is lower than both km and ke.

Discussion

- Theoretical and modelling results of ETC for Li_2TiO_3 pebble bed is obtained for 2D pebble bed (with 78.5 % packing fraction), mono-sized pebble bed (with 52.3 % packing fraction) and binary-sized pebble bed (with 65.8% packing fraction) from these results, it can be seen that the packing fraction is an important parameter for enhancing the ETC value of Li_2TiO_3 pebble bed.
- Modelling results is quite different form the experimental results of binary-sized pebble bed, this is possible because of the modelling result is obtained by using simple and regular configuration of pebble bed while the experimental results are always based on complex and irregular geometrical configuration of pebble bed.
- The modelling results of binary-sized bed is estimated by using heat conduction mode only, while in the experimental results in addition to heat conduction mode the other modes of heat transfer may also present.

Conclusions

- Theoretical results and modelling results for ETC of Li_2TiO_3 pebble bed have been estimated.
- Modelling results of ETC for Li_2TiO_3 pebble bed is successfully carried out by COMSOL 4.3 and compared with available experimental data.
- Approximate estimation of ETC of Li_2TiO_3 pebble bed is successfully done without experimental test facility at present.
- The theoretical and modelling results of ETC are based on thermal conduction model, so other mode of heat transfer needs to be added, and that will carried out in next work.

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