5th International Conference on Porous Media and Their Applications in Science, Engineering and Industry

Refereed Proceedings

Summer 6-26-2014

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Proceedings of the 5th International Conference on Porous Media and its Applications in Science and Engineering
ICPM5
June 22-27, 2014, Kona, Hawaii

COMPARISON OF VOLUME-AVERAGED SIMULATION AND PORE-SCALE SIMULATION OF THERMAL RADIATION AND NATURAL CONVECTION IN HIGH TEMPERATURE PACKED BEDS

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ABSTRACT

The phenomenon of natural convection and thermal radiation heat transfer in fluid-saturated high temperature packed beds has been widely studied due to its various applications ranging from solar collectors to high temperature gas cooled reactor. With the local thermal non-equilibrium model, the majority of the numerical simulation studies on natural convection and radiation heat transfer in fluid-saturated porous media have limits. In these studies the internal heat transfer coefficients have always been calculated as the existing formulas, which were obtained by the experiments of forced convection in porous media [1-2]. However, natural convection heat transfer in porous media is dominated by the temperature difference between solid particles and fluid, which is different with the forced convection in porous media. For thermal radiation in porous media, the Rosseland diffusion approximation model has always been used in simulations by researchers [3-4], in which the mean absorption coefficient are not calculated according to the experiments and need to be determined by ray-tracing Monte Carlo simulations. Based on high temperature packed pebble beds, this study is aimed to compare the volume-averaged simulations and pore-scale simulations of high temperature packed beds, and predict the effective thermal conductivities of packed beds with temperature up to 1600℃.

The effective thermal conductivities of the pebble beds under different temperatures are essential parameters in simulation models to analyze the maximum fuel temperature and temperature distribution in the reactor core in the reactor safety analysis. The SANA test facility was installed at the Research Centre, Julich in Germany specifically to investigate the heat transport mechanisms inside the core of a high temperature gas cooled reactor (HTGR). The validation of the volume-averaged approach and pore-scale approach are based on the experimental data of SANA test [5].

In high temperature helium-saturated annular packed pebble bed, the inner wall has a heat source and the outer wall is isothermally cooled at a lower temperature. The top and bottom walls are kept adiabatic. In the volume-averaged simulations, local thermal non-equilibrium model with the revised internal heat transfer coefficients and radiative heat flux is applied as the energy equation, and no uniform porosity distribution is used. To describe the random packed structure, PFC 3D software is used to simulate the spheres packing, which is used for direct pore-scale numerical simulations. Natural convection and thermal radiation in a 2D circular cross section of the annular pebble bed have been carried out. The effective thermal conductivities and temperature distributions of volume-averaged and pore-scale simulations of the high temperature helium-saturated annular packed pebble bed are corresponded well with the existed experimental data with temperature below 1000℃, and predict the effective thermal conductivities of the pebble bed core with temperature up to 1600℃, which are vital references for thermal hydraulic designs of high temperature gas cooled reactor core.

INTRODUCTION

Packed beds are widely used in variety of industries, such as catalytic reactors, absorption towers, packed bed regenerators and high temperature gas-cooled reactors. The heat transfer in an enclosure with high temperature packed beds have been gaining interest, because exploring the coupled mechanism of conduction, natural convection and thermal radiation in high temperature packed bed enclosures aids in improving the design of many applications.

There are two main approaches for the CFD simulation of the geometry of the closely packed beds: the volume-averaged approach and the pore-scale approach. In the volume-averaged approach, an averaged concept of porosity is applied to simulate the closely packed geometry. As the internal heat transfer between solid particles and fluid is small because of natural convection in the enclosure, the temperature difference between solid and fluid cannot be ignored. So the local thermal non-equilibrium model is quite necessary for high temperature packed beds in an enclosure. Reda [6] has carried out the experimental investigation of a finite vertical cylinder with a heat source at the inner and constant temperature at the outer. The results showed that the radial temperature drop across the annulus was found to systematically depart from the finite-length cylinder as heat power was increased. Rajamani et al [7] have studied the natural convective heat transfer in an annular cylinder embedded with porous medium and discussed the effect of aspect ratio and radius ratio of the annulus on the heat transfer rate. Raptis [8] has investigated the heat transfer behavior of vertical plate in porous medium subjected to constant suction velocity. Inspired by electric heating elements, Yih [9] has studied the effect of radiation on natural convection in a vertical cylinder embedded with porous medium. Cherif and Sifaoui [10] have considered radiation along with conduction and convection to predict the heat transfer behavior in a cylindrical enclosure. The problem of heat transfer in saturated porous vertical annulus with combined effect of radiation and convection has been studied by Badruddin et al. [11]. Hossain et al [3] has studied numerically the combined effect of conduction-convection-radiation on natural convection flow of an optically thick Newtonian fluid with gray radiant properties, confined in a porous media square cavity. In these studies, the internal heat transfer coefficients have always been calculated as the existing formulas of local velocity. For thermal radiation, the Rosseland diffusion approximation model has always been used in simulations in which the mean absorption coefficient are not calculated according to the experiments and need to be determined by ray-tracing Monte Carlo simulations for application simulations. The problem of heat transfer in porous annular cylinder requires attention as it has many practical applications such as gas cooled reactor vessels, and it is necessary to revise and apply the volume-averaged approach with local thermal non-equilibrium model to applications, such as the SANA test.

With the dramatic progress in computational capability, a pore-scale approach for packed beds has been adopted by many researchers to simulate the distribution characteristics of gas flow and temperature within closely random packed beds, whose geometry is realistically modeled in the simulations. For natural convection in packed bed, Merrikh and Lage (12-13) have studied natural convection in a differentially heated square enclosure filled with discrete conducting square solid blocks. The study covered fluid Rayleigh number (Ra) from 10^5 to 10^8 and fluid-to-solid thermal conductivity ratio κ from 0.1 to 10. Good agreement between the continuum and porous-continuum model results. Braga and de Lemos [14] has analyzed laminar natural convection in regularly distributed particles with different geometry. Pourshaghaghy et al. [15] have studied a porous medium formed by a number of randomly distributed solid obstacles. Porous media and packed bed are usually regarded as semi-transparent media with certain optical thickness, which is obtained by ray-racing Monte Carlo method [16]. Cheng et al [17] have proposed a new approach to calculate the radiation heat transfer in a packed bed from its structure using the Voronoi network model and evaluated the effective thermal conductivity by taking into account the effect of the radiation heat transfer. The coupled simulation of natural convection and thermal radiation in packed beds by CFD are rarely except that transient heat transfer by free convection in a simple cubic sphere packed structure has studied by Laguerre et al [18] experimentally and numerically. However, this study is aimed to simulate the pore-scale of the natural convection, conduction and thermal radiation coupled heat transfer in random packed beds by CFD software.

NOMENCLATURE

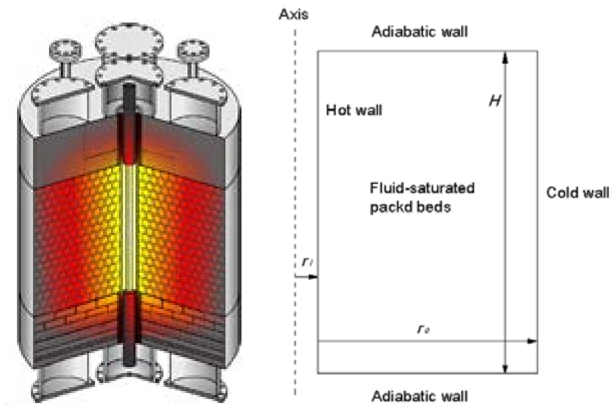
r	=	Radius, m
d	=	Diameter, m
H	=	Height of packed bed, m
k	=	thermal conductivity, W/m·K
F	=	Inertia coefficient constant
H	=	Height of packed bed, m
c_p	=	Isobaric specific heat, J/kg·K
T	=	Temperature, K
z	=	Coordinate in axial direction, m
u	=	Pore velocity in radial direction, m/s
w	=	Pore velocity in axial direction, m
h_v	=	Volumetric heat transfer coefficient
λ_d	=	Thermal dispersion coefficient
E	=	Young's modulus, Pa
Ra	=	Rayleigh number
Q	=	heat flux, W
Greek Symbols		
ε	=	Porosity
ρ	=	Density, kg/m^3
ρ	=	Density
μ	=	Viscosity, Pa· s
Subscripts		
i	=	Inner
o	=	Outer
p	=	Particle
eff	=	Effective
f	=	Fluid
s	=	Solid
b	=	Bulk
stag	=	Stagnant
m	=	Mean
Superscripts		
*	=	effective

1 Models of computation

1.1 Volume-averaged model

1.1.1 Physical models

In this work, the revised volume-averaged model for high temperature packed beds have to be validated by experimental results obtained from the SANA test facility, shown in Fig. 1(a). The test facility consisted of a central heating element. The inner radius r_i of the pebble bed is 0.07m, the inner radius r_o is 0.75m and the height is 1.0 m. The top and bottom of the facility is well-insulated. For the tests conducted with the 60mm diameter graphite pebbles, measurements were taken of the pebble temperatures at different radial positions close to the bottom of the pebble bed (height 90 mm) as well as at the center (height 500 mm) and top (height 910 mm). Considering the axial symmetry of the pebble bed, only the cross section of the vertical annular is used for simulation with the real size, as shown in Fig. 1(b). Both in the two steady models, the top and bottom walls are adiabatic. The inner wall is constant heat flux, whereas the outer wall is constant temperature according to the experimental data. The temperature dependent material properties of helium are as prescribed by the nuclear safety standards commission (KTA, 1983). The thermal properties of graphite are referred to the experiment SANA test results.



(a) SANA test [5] (b) Computational model

Figure 1: SCHEMATIC OF SANA TEST AND COMPUTATIONAL MODEL

1.1.2 Governing equations

In this work, accounting for the spatial non-uniform porosity distribution of pebble bed, the volume-averaged model is consist of Darcy – Brinkman – Forchheimer model and local thermal non-equilibrium model to describe the momentum and energy transportation.

Continuity equation

$$\frac{1}{r}\frac{\partial(r\varepsilon u)}{\partial r}+\frac{\partial(\varepsilon w)}{\partial z}=0 \tag{1}$$

Momentum equation

$$\begin{aligned}\frac{1}{r}\frac{\partial(r\rho_f\varepsilon uu)}{\partial r}+\frac{\partial(\rho_f\varepsilon wu)}{\partial z}=-\frac{\partial(\varepsilon p)}{\partial r}\\ -\varepsilon^2\frac{\mu_f}{K}u-\varepsilon^3\frac{\rho_f F}{\sqrt{K}}\sqrt{(u^2+w^2)}u\\ +[\frac{1}{r}\frac{\partial}{\partial r}(\varepsilon r\mu_f\frac{\partial u}{\partial r})+\frac{\partial}{\partial z}(\varepsilon\mu_f\frac{\partial u}{\partial z})]\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{1}{r}\frac{\partial(r\rho_f\varepsilon uw)}{\partial r}+\frac{\partial(\rho_f\varepsilon ww)}{\partial z}=-\frac{\partial(\varepsilon p)}{\partial z}\\ -\varepsilon^2\frac{\mu_f}{K}w-\varepsilon^3\frac{\rho_f F}{\sqrt{K}}\sqrt{(u^2+w^2)}w\\ +[\frac{1}{r}\frac{\partial}{\partial r}(\varepsilon r\mu_f\frac{\partial w}{\partial r})+\frac{\partial}{\partial z}(\varepsilon\mu_f\frac{\partial w}{\partial z})]+\varepsilon\rho g\end{aligned} \tag{3}$$

Energy equation

Fluid

$$\begin{aligned}\frac{1}{r}\frac{\partial(r\rho_f c_p\varepsilon uT_f)}{\partial r}+\frac{\partial(\rho_f c_p\varepsilon wT_f)}{\partial z}=h_v(T_s-T_f)\\ [\frac{1}{r}\frac{\partial}{\partial r}(\varepsilon^*k_f+\lambda_d)r\frac{\partial T_f}{\partial r}]+[\frac{\partial}{\partial z}(\varepsilon^*k_f+\lambda_d)\frac{\partial T_f}{\partial z}]\end{aligned} \tag{4}$$

Solid

$$\begin{aligned}[\frac{1}{r}\frac{\partial}{\partial r}(r(1-\varepsilon^*)k_s\frac{\partial T_s}{\partial r})+\frac{\partial}{\partial z}((1-\varepsilon^*)\frac{\partial T_s}{\partial z})]\\ -h_v(T_s-T_f)-\frac{1}{r}\frac{\partial}{\partial r}(rq_{rad})-\frac{\partial}{\partial z}(q_{rad})=0\end{aligned} \tag{5}$$

The porosity distribution [19]

$$\begin{aligned}&\varepsilon(z)=2.14z^2-2.53z+1(z\le 0.637)\\ &\varepsilon(z)=\varepsilon_b+0.15\exp(-0.9)\\ &+0.29\exp(-0.6z)\times\cos(2.3\pi(z-0.16))\\ &(z>0.637)\end{aligned} \tag{6}$$

$$z=\begin{cases}(r-r_i)/d_p, r_i<r<(r_i+r_o)/2\\ (r_o-r)/d_p, (r_i+r_o)/2<r<r_o\end{cases}$$

The permeability K and geometric function F of packed beds are based on Ergun's model [20] as

$$K=\frac{\varepsilon^3 d_p^2}{150(1-\varepsilon)^2},\quad F=\frac{1.75}{\sqrt{150\varepsilon^{3/2}}} \tag{7}$$

The internal heat transfer coefficient is different from others researchers, who always use the relations of Re number. It is reasonable to adopt the heat transfer coefficient of natural convection along a sphere [21].

$$h_{sf}=k_f(2+0.428(Ra)^{1/4})/d_p \tag{8}$$

A multi-sphere unit cell model derived by Van Antwerpen [22], which considers both short and long radiation in pebble beds, is adopted for the simulations.

The effective porosity [23] $\varepsilon^*=\dfrac{k_s-k_{stag}}{k_s-k_f}$ (9)

The stagnant thermal conductivities as followed is derived by the results of Zehner [24]

$$k_{stag}=k_s\sqrt{(1-\varepsilon)}(\frac{0.75F\cdot r_p}{E_p})^{2/3}/r_p \tag{10}$$

Where the force between the spheres [25]

$$F=72.307Z_{depth}+7.8716$$

Z_{depth} is the distance from the bottom wall.

The thermal dispersion coefficient [26]

$$\begin{aligned}&\lambda_d=C(\rho c_p)_f d_p\sqrt{u^2+w^2}(1-\varepsilon)\\ &C=1.042[\rho_f c_p d_p u(1-\varepsilon_m)]_0^{-0.8282}\end{aligned} \tag{11}$$

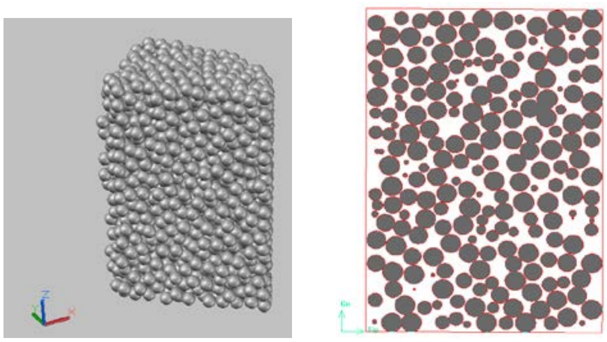
1.1.3 Numerical method

Computations with 6800 structured grids after grid independence test are carried out using Fluent 6.3.2, a commercial CFD code. The SIMPLE algorithm is used to couple the pressure and velocity. And PRESTO! (PREssure Staggering Option) scheme is used for pressure discretization and second-order discretization scheme is used for advection and energy terms. The convergence criteria are that mass flow rate and the total heat transfer flux are possible small.

1.2 Pore-scale model

1.2.1 Physical models

Because of the random structure of the graphite spheres packing, it is reasonable to generate a random packed bed with the same mean porosity. PFC 3D is a commercial software based on DEM (Discrete element method), which is able to generate a random packing of pebble bed by calculating the interaction forces of thousands of spheres until the forces equilibrium are reached. According the size of the test, thousands of graphite spheres are packed randomly, as shown in Fig. 2. However, the mesh generation at the point contact is a crucial issue when carrying out the simulation with conventional CFD methods. One cross section with the same mean porosity as the whole packed bed is used for the pore-scale simulations to simplify the problem.



(a) 3D random packed bed (b) Cross section

Figure 2: RANDOM PACKED BED FROM PFC3D

1.2.2 Governing equations

The natural convection in the packed bed is laminar. And discrete ordinates radiation model is used to describe the thermal radiation in the packed bed with transparent Helium and opaque graphite spheres with emissivity 0.8. The governing equations are the default equations in Fluent. The top and bottom walls are adiabatic. The inner wall is constant heat flux, whereas the outer wall is constant temperature according to the experimental data.

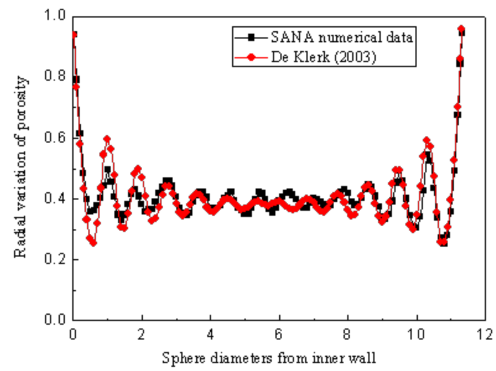
1.2.3 Numerical method

Computations with 231372 unstructured grids after grid independence test are carried out using Fluent 6.3.2, a commercial CFD code. The SIMPLE algorithm is used to couple the pressure and velocity. And PRESTO! (PREssure Staggering Option) scheme is used for pressure discretization and second-order discretization scheme is used for advection and energy terms. The convergence criteria are that mass flow rate, the total heat transfer flux and radiation heat transfer rate is possible small.

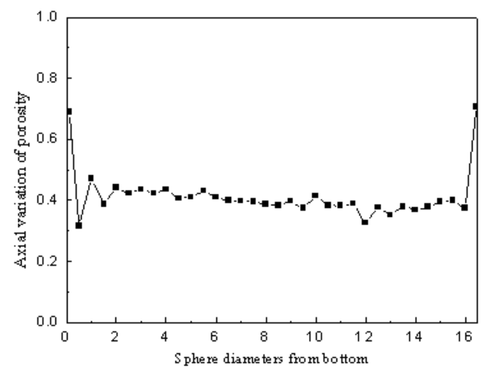
2 Results and discussions

2.1 Porosity distribution comparison

The porosity distribution of the generated annular packed bed with the porosity 0.41 is shown in Fig. 4. The simulation results by PFC 3D are corresponded well with the oscillatory correlation [19] about variation in the radial direction in the porosity of packed beds. The slight difference near the inner wall can be attributed to the fact that there are not enough spheres when the porosity of the only 45 degrees in the circumferential direction is calculated. It can also be said that there appears to be very little difference between the variations in the porosity near the outer wall. The second graph in Fig.3 shows that the damped oscillatory behavior of the porosity at axial direction is weaker than that of radial direction due to the height is larger than the radius.



(a) Radial variation of porosity



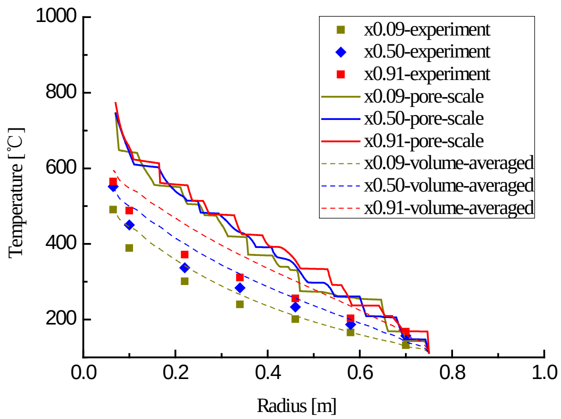
(b) Axial variation of porosity

Figure 3: POROSITY DISTRIBUTION OF RANDOM PACKED BED

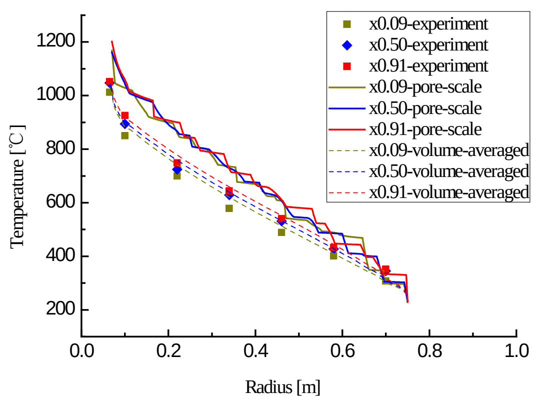
2.2 Temperature distribution comparison

With the same heat source (10kW, 30kW), the temperature distribution along the radius direction at different height of pore-scale simulation and volume-averaged simulation are compared with the experimental data. It shows that the temperatures of pore-scale simulations are much higher than the experimental data, because graphite spheres are not completely contacted and the heat needs to be transferred by the weak natural convection and radiation, especially near the inner wall. The volume-averaged simulation results are corresponded better with the experimental data. It reveals that the volume-averaged model built is proper to simulate the natural convection, conduction and thermal radiation in high temperature packed bed, and is also a timesaving simulation method to predict the effective thermal conductivities above the temperatures of the existed experiments.

assumption of the incomplete contact among spheres and between spheres and the wall in the 2D packed bed.



(a) Temperature distribution (10kW)



(b) Temperature distribution (30kW)

Figure 4: COMPARISON OF TEMPERATURE DISTRIBUTION

2.3 Effective thermal conductivities prediction

The total effective conductivity in the radial direction of the annular packed bed can be calculated from

$$k_{eff,total} = \frac{Q \ln(r_o / r_i)}{2\pi H (T_h - T_c)} \tag{12}$$

The effective thermal conductivity dependent of temperature can be extracted as

$$k_{eff}\Big|_{r_j}^{r_{j+1}} = \frac{Q \ln(r_{j+1} / r_j)}{2\pi H (T_{j+1} - T_j)} \tag{13}$$

When the above equation is used, one sphere diameter is selected as the computation cell length to decrease temperature fluctuation due to the porosity variation near the wall. The effective thermal conductivities calculated from volume-averaged model and pore-scale model are compared with the experimental results in Fig. 5. It shows that the volume-averaged model predicts the thermal conductivities very close to the real value, except that the effective thermal conductivity at high temperature is smaller. It's mainly because of the MSUC radiation model is not very accurate in the wall region if the curvature of the wall is large compared to the sphere diameter. The results of the pore-scale model are much smaller because of the

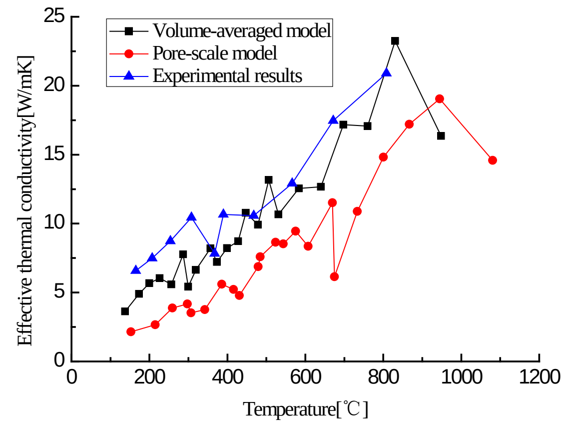


Figure 5: COMPARISON OF TEMPERATURE-DEPENDENT EFFECTIVE THERMAL CONDUCTIVITIES

By the above analysis, the volume-averaged model has been validated as the more precise and simpler model to predict the effective thermal conductivities of annular pebble bed tests with the inner wall is 1600 ℃ and the outer wall is 1400 ℃. The inner radius r_i of the pebble bed is 0.5 m, the inner radius r_o is 2.0 m and the height is 1.0 m. The total effective thermal conductivity of this pebble bed is 45.95 W/mK, and the effective thermal conductivities with different high temperature are calculated by Eq. 13, as shown in Fig. 6. And it also reveals that the radiation effective conductivities play a vital role in the heat transfer.

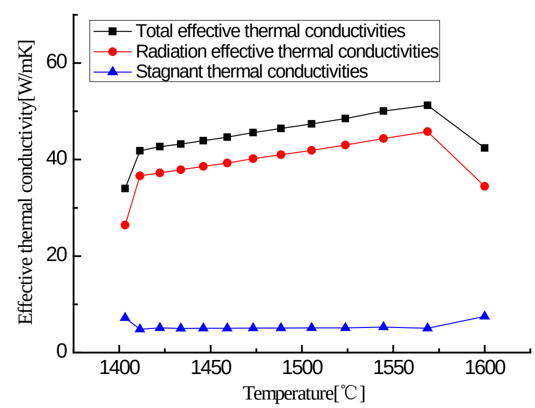


Figure 6: THE EFFECTIVE THERMAL CONDUCTIVITES IN ANNULAR PEBBLE BED WITH TEMPERATURE 1400 ℃~1600℃

CONCLUSIONS

By the comparison of volume-averaged model and pore-scale model simulation results with the same experimental heat source (10kW, 30kW), the volume-averaged model is more timesaving and more precise than the pore-scale model according to the experimental results. The volume-averaged model has been used to predict the effective thermal conductivities of annular pebble bed tests with higher temperature, will be very important references for thermal hydraulic designs of higher temperature gas cooled reactor core.

ACKNOWLEDGEMENT

We would like to acknowledge supports by International Science & Technology Cooperation Program of China (2012DFG71950)，the Research Project of Chinese Ministry of Education. (No.113008A) and Beijing Higher Education Young Elite Teacher Project (YETP0092).

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