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MULTIPHYSICS METHODS DEVELOPMENT FOR HIGH TEMPERATURE GAS COOLED REACTOR ANALYSIS

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ABSTRACT

Gas cooled reactors have been characterized as one of the most promising nuclear reactor concepts in the Generation-IV technology roadmap. Considerable research has been performed on the design and safety analysis of these reactors. However, the codes and methods being used to perform these analyses are not state-of-the-art and are not capable of performing detailed three-dimensional analyses. This paper presents the results of an effort to develop an improved thermal-hydraulic solver for the pebble bed type high temperature gas cooled reactors. The solution method is based on the porous medium approach and the momentum equation including the modified Ergun's resistance model for pebble bed and energy equation in two temperature model are solved in three-dimensional cylindrical geometry. A preliminary verification was performed by comparing the results with the experiments conducted at the SANA test facility. Various experimental cases are modeled and good agreement is observed. The 3-D thermal-hydraulics code was then coupled to the 3-D spatial kinetics code, PARCS, to perform coupled reactor simulations. The verification of the coupled code system was performed by analyzing the steady state and transient cases of the OECD/NEA PBMR-400 benchmark problem.

INTRODUCTION

Vast amount of research has been performed on the heat transfer and fluid flow through packed beds in many areas of the chemical and mechanical engineering. The applications in nuclear reactor engineering base the research that was done in these areas.

A common practice to model the heat transfer through the pebble bed is considering the existence of local thermal equilibrium (LTE) between the two mediums. This assumption results in solving a single energy equation and is valid for the applications where the temperature gradient between the two mediums is negligible. The validity of LTE condition was investigates by several researchers and conditions of departure from LTE were stated. [1,2]. The temperature difference between the solid fuel pebbles and the gas coolant in a pebble bed nuclear reactor is significantly high which requires the modeling of heat transfer with a consideration of local thermal non-equilibrium (LTNE). Almost all the research studies considered the LTNE condition and modeled the heat transfer with separate energy equation for each medium [3,4].

In most investigations, the momentum equation was solved using Ergun's correlation in order to take the inertia and viscous effects. Ergun's correlation was proven to be valid for most of the applications in chemical industry [5]. The mass flow rates, so the Reynolds numbers, in these applications are relatively small compared to those observed in PBRs. It was shown in many studies that the pressure drop across the pebble bed core is over-predicted with the use of Ergun's correlation [6,4]. Figure 1 shows the comparison of pressure drop values versus Reynolds number calculated with three different models. Among these three models, KFA's modified Ergun correlation provides the best prediction.

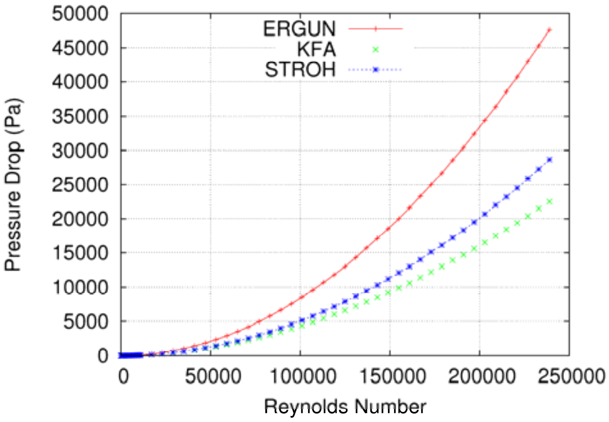

Figure 1. Pressure Drop Models

DESCRIPTION OF THE ACTUAL WORK

The physical and mathematical model for the flow and heat transfer in the pebble bed is based on the porous medium approach.[7] The heat transfer is modeled considering the local thermal non-equilibrium between the solid and gas, which results in two separate energy equations (Eq. 1 and Eq. 2) for each medium.

Solid Medium:

$$\frac{\partial}{\partial t}\left[(1-\varepsilon)\rho_s c_{p_s} T_s\right] = \nabla.(1-\varepsilon)\,k_s \nabla T_s - \alpha(T_s - T_f) + Q \qquad (1)$$

Gas Medium:

$$\frac{\partial}{\partial t}\left[\varepsilon \rho_f c_{p_f} T_f\right] + \nabla.\left(\rho_f c_{p_f} u T_f\right) = \nabla.\left(\varepsilon k_f \nabla T_f\right) - \alpha\left(T_f - T_s\right) \qquad (2)$$

Where, indexes *s* and *f* indicate solid and fluid, respectively. ρ, ε, c_p, k, α and u are density, porosity, specific heat, effective thermal conductivity, solid-to-fluid heat transfer coefficient and fluid velocity, respectively. The effective thermal conductivity of the pebble bed can be calculated both from Zehner - Schluender and Robold correlations. As depicted in Figure 2, the effective thermal conductivity of the bed is strongly dependent on the temperature and fast neutron dose.

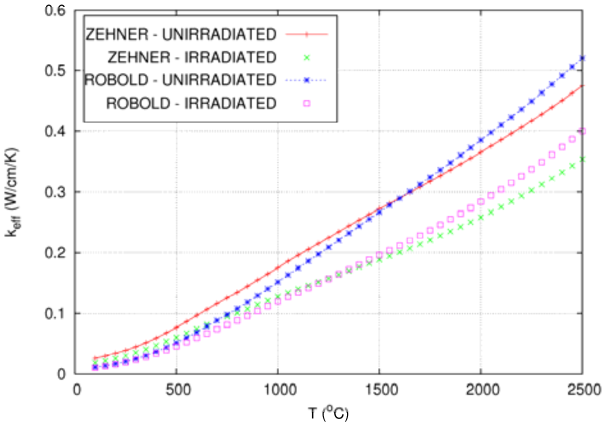

Figure 2. Effective Conductivity of Pebble Bed

The fluid flow is modeled by the mass and momentum equations (Eq. 3 and Eq. 4) derived for packed beds and considering the modified Ergun's resistance model.

Continuity Equation:

$$\frac{\partial}{\partial t}\left(\varepsilon\left\langle\rho_f\right\rangle^f\right)+\nabla.\left(\left\langle\rho_f\right\rangle^f\left\langle v_f\right\rangle\right)=0 \tag{3}$$

Momentum Equation:

$$\frac{\partial}{\partial t}\left(\left\langle\rho_f\right\rangle^f\left\langle v_f\right\rangle\right)=-\nabla\left\langle P_f\right\rangle+\varepsilon\left\langle\rho_f\right\rangle^f\vec{g}$$
$$-160\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu}{d^2}\left\langle v_f\right\rangle \tag{4}$$
$$-3.0\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho}{d}\frac{\left\langle v_f\right\rangle\left\langle v_f\right\rangle}{(\mathrm{Re}/(1-\varepsilon))^{0.1}}$$

where d is the diameter of the pebble and Reynolds number, *Re*, is given by the following expression.

$$\mathrm{Re}=\frac{\rho V d}{\mu} \tag{5}$$

The fluid flow and heat transfer described with Eqs. 1-4 are modeled in three dimensional cylindrical coordinates and can be solved in steady-state and time dependent. The spatial discretization is performed using the finite volume method over the control volume shown in Figure 3. The theta-method is used for the temporal discretization.

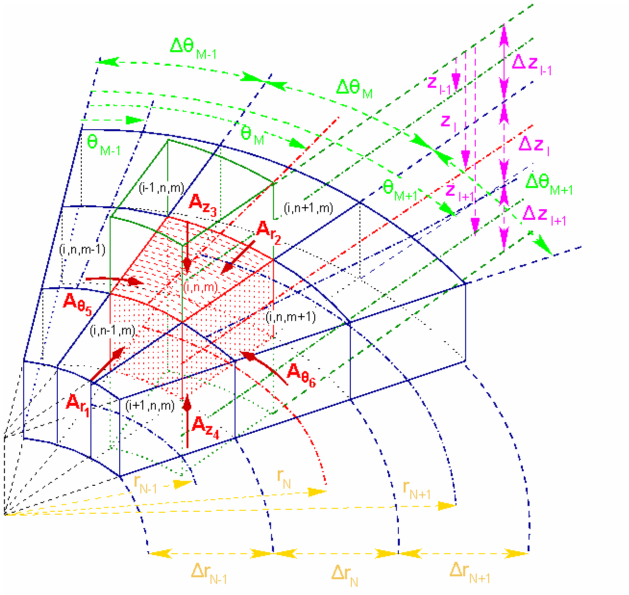

Figure 3. Cylindrical Control Volume

The convective terms are discretized using a general scheme which enables to choose one from several different schemes such as, central differencing, upwind, hybrid, power law and exponential schemes as described by Patankar [9].

The linear system obtained from the discretization of the energy and momentum equations are either symmetric or asymmetric. Therefore, several iterative and direct schemes were implemented in the code. Preconditioned Conjugate Gradient (PCG) and Generalized Minimum Residual (GMRES) are the two major solvers.

RESULTS

A preliminary verification of the 3-D thermal hydraulics code was performed by comparing the simulation results with the experiments conducted at the SANA test facility [8]. This facility is located at the Institute for Safety Research and Reactor Technology (ISR), Julich, Germany. Figure 4 shows the core of the test facility. Various experimental cases are modeled and good agreement with the experimental data is observed. Figure 5 – 8 show the comparison of the experimental data with the numerical results.

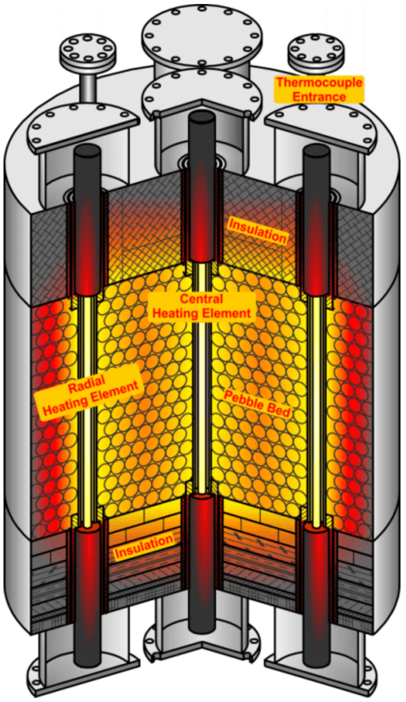

Figure 4. Sana Test Core

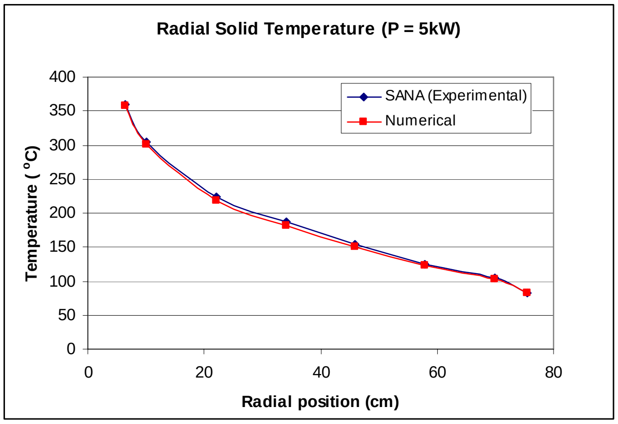

Figure 5. Radial temperature profile at 5kW

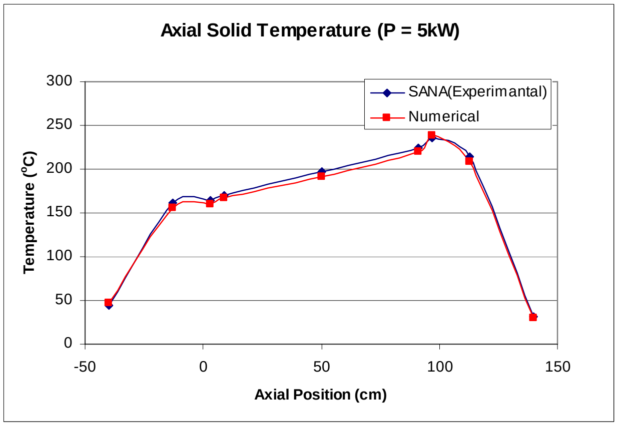

Figure 6. Axial temperature profile at 5kW

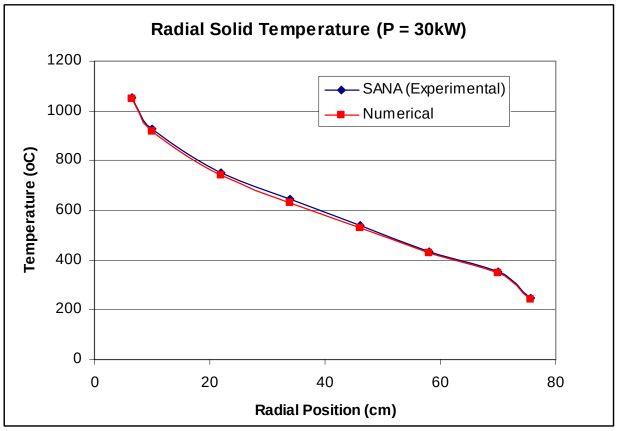

Figure 7. Radial temperature profile at 30kW

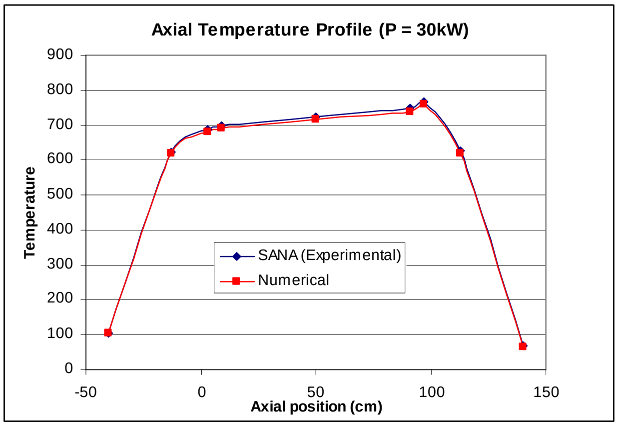

Figure 8. Radial temperature profile at 30kW

The steady-state coupled neutronics-thermalhydraulics problem of PBMR-400 benchmark was analyzed with the coupled code system[11]. Figure 9 and 10 show the comparison of the results with the ones obtained from the KAERI calculations. A good agreement is obtained.

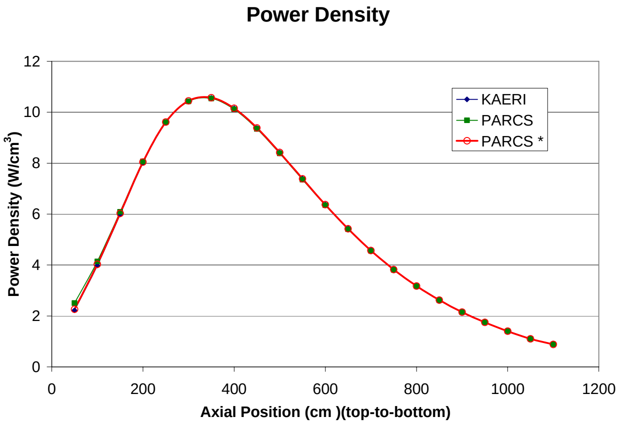

Figure 9. Axial power density profile

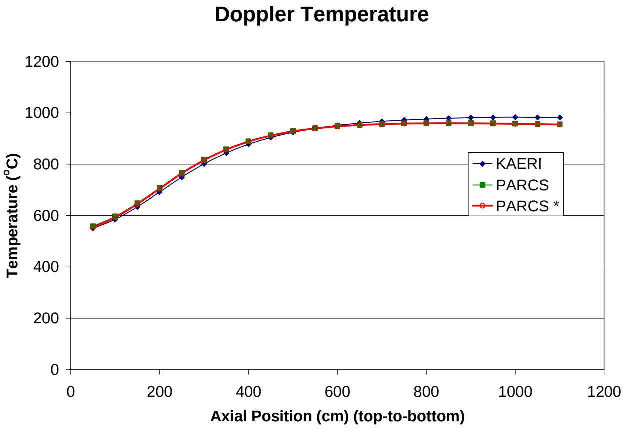

Figure 10.Axial Doppler temperature profile

CONCLUSION AND FUTURE WORK

A three dimensional thermal hydraulic solver for pebble bed reactors was developed. The preliminary verification was performed with the simulation of the SANA experiment. A good agreement with the experimental data is achieved.

In order to perform three dimensional design and safety analysis, the developed thermal-hydraulics code was coupled to the spatial kinetics code PARCS which provides the solution of the neutron diffusion equation in three dimensional cylindrical coordinates [10]. The validation of the coupled code system was performed with the analysis of steady-state coupled neutronic-thermalhydraulics problem. An on-going effort is to model the control rod ejection scenarios as described in the OECD/NEA/NSC PBMR-400 benchmark problem.

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