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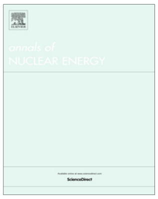

An improved porous media approach to thermal–hydraulics analysis of high-temperature gas-cooled reactors

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ABSTRACT

A precise thermal–hydraulics model is of great importance for developing more effective designs of High Temperature Gas Cooled Reactors (HTGR). Recently, several advancements have been made in the methods of analysis of porous media which could be of significant value in the development of more precise and robust codes. The objective of this research is to incorporate some of the most recent improvements in the development of a new 2D program for thermal–hydraulics analysis of modular high temperature reactors. The program is mainly based on the solution of a coupled set of mass, energy and momentum conservation equations for the gas flow, along with the energy conservation equation in the solid. The energy conservation has been cast for non-equilibrium conditions. A suitable implementation could enable the program to handle both well-known types of HTGR, namely the pebble bed and prismatic. To this aim, an appropriate set of constitutive equations for effective heat conductivity of solid, pressure drop, and heat transfer coefficient were used for each reactor type. One should be aware of the specific case of effective heat conductivity according to its importance in the analysis where its dependence on temperature and dose should be considered. Moreover, two distinct models have been adapted for a better estimation of effective heat conductivity. The finite-volume method has been used for numerical solution of the conservation equations and the Rhie-Chow technique has been utilized to overcome the discretization problems regarding pressure gradient. This technique obviates the need for staggered grid and will directly result in reduction of computational cost.

The validity of the developed program which is referred to as Thermo Hydraulics Porous Program (THPP) has been verified thoroughly. A set of experimental and numerical benchmark problems for both cases of HTGRs have been reported to show applicability and validity of the code. The results are generally in good agreement except for a few specific cases discussed in the paper.

1. Introduction

Leading to the satisfying of future demands for energy, it is forecast that high temperature modular reactors (HTR) will be selected as the next reactors generation. Among the most prominent features of these kinds of reactors, one can allude to their inherent safety as well as ease of design, function and maintenance. As regards accidents and failures, the need for any external safety sources is obviated as such reactors are inherently safe. As against its inherent characteristics, Physical properties of this type of reactors are the only factors affecting it; yet, a lot of other hazardous conditions are avoided. Apart from being inherently safe, the other advantage of this reactor is its being economically designed; hence, this is regarded as a competitive advantage.

Reliable simulation of heat transfer, neutronic cases and fluid flow are prerequisites to the designing and developing of the HTRs next generation. THERMIX introduced by Julich research center in Germany is the mostly known and approved tool worldwide, from among various current thermo-hydraulic tools for HTRs design and safety analysis (Petersen, 1984). Also the nuclear energy and energy systems institute (IKE) employs a version of THERMIX (with some upgrades and wider applicability for various HTRs designs, accompanied by neutronics code system ZIRKUS) (Ben Said et al., 2006; Bernnat and Feltes, 2003). THERMIX is a code with two dimensions. Generally, such modeling is based on computational fluid dynamic (CFD) commercial codes. Becker and Laurien (2003), for example, made use of CFX4 code for the modeling. Lee et al. (2007) investigated the turbulence-induced heat transfer in a pebble bed reactor core, in which the spherical fuel pebbles were randomly distributed in the core. Their result's showed that the turbulent structure of the coolant was better resolved up to

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the grid scale with the LES method, while only the dominant flow structures were resolved with the RANS method. Bai et al. (2011) conducted an experimental study on the pressure drop of the single-phase and the air–water two-phase flow in the bed of rectangular cross sections filled densely with uniform spheres. Their improved correlations were obtained based on the previous study considering the single-phase pressure drops for finite pebble beds with spherical and non-spherical particles. A new empirical correlation for the prediction of two-phase flow pressure drops has been recently proposed based on the gas phase relative permeability as a function of the gas phase saturation and the void fraction. Pilehvar et al. (2013) investigated the effect of compressible flow in spherical fueled reactors using the porous media model. The coolant compressibility has been introduced as an effective parameter in the thermal–hydraulic analysis in their study. The reactor core was simulated and thermal–hydraulic parameters of the core were obtained through Computational Fluid Dynamic (CFD) approach. They compared the results obtained by other codes. The outcomes showed that the inclusion of compressibility was reasonable and would lead to a slight difference between the measured and actual temperature, pressure, and velocity. Cho et al. (2009) described a homogenization model which not only is easy to implement but also gives a more realistic temperature distribution in a fuel pebble, providing the fuel-kernel and graphite-matrix temperatures separately. They performed steady-state and transient thermal analyses using this model, and the point kinetics model is then coupled with the homogenization model to incorporate fuel-kernel temperature feedback.

The present work aims to develop a 2D thermo-hydraulic analysis tool with the following advantages:

- applicability in simulation of 2D geometry,
- ability of coupling with a neutronic tool to gain neutronic and thermo-hydraulic feedback,
- provision of adequate physical description to solve issues on design and safety considerations,
- high speed performance; i.e. the simulation time is short enough such that a fast analysis resulting from a change in design or parametric study is possible,
- applicability for different designs of HTRs, including pebble bed and block types.

In this work, the capability of THPP for the simulation of pebble bed and block type reactors is shown. In the above mentioned works, the key weak point is that they generally use Zehner and Schlünder (1972) to model effective conduction heat transfer coefficient. However, in the present work Quasi-homogeneous model of Vortmeyer and Robold is employed in addition to the foresaid model while they can easily inter exchanged. Furthermore, here the effect of Fast Fluence/Neutron Doses has been well applied to the model. In order to decrease computational costs and achieve better convergence, Rhie-Chow technique is used rather than the commonly used staggered grids.

Hossain et al. (2008) simulated two adjusted benchmark problems related to pebble bed and block type reactors and compared the results to that of THERMIX & TH3D thermo-hydraulic codes. Finally, thermo-hydraulic analysis has been performed on different types of pebble bed and block type reactors in their normal condition.

2. Mathematical model and governing equations

2.1. Continuity equations

The solid phase inside the reactor (e.g. fuel, reflector, flow channels, etc.) is considered as fixed and the coolant gas flows around the solids. The time-dependent compressible mass conservation equation for gas is solved only in the part of the reactor where flow exists. These equations are known as continuity equations like as follows:

$$\frac{\partial(\varepsilon\rho c_i)}{\partial t} + \nabla.(\varepsilon\rho\vec{u}c_i) = 0 \qquad (1)$$

where ε defines the partial volume of the gas phase in the control volume, ρ is the gas density, $\vec{u}$ the velocity, and c_i is the volume fraction of the ith gas component in the gas phase.

2.1.1. Momentum equation

Similar to the continuity equation, the conservation of momentum is only solved in the parts of reactor where flow exists. When u is the velocity vector in the x direction, the momentum equation for Newtonian fluids is written as

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla.(\rho u\vec{u}) = \nabla.(\mu\nabla u) - \frac{\partial p}{\partial x} + V_x - R_x - \gamma\rho g \qquad (2)$$

The terms on the left hand side of the equation are the unsteady and convection terms respectively, while the terms on the right hand side represent diffusion of momentum, pressure gradient, viscous term that are in addition to the diffusion term, the pressure drop due to solid–fluid friction, and the body force due to gravity in the corresponding direction per unit volume, respectively. A simplified quasi steady momentum conservation equation is written as

$$\varepsilon\nabla.(p) = -R + \varepsilon\rho g \qquad (3)$$

where p is the system pressure, g is the gravitational constant, and R represents the friction force between gas–solid phases. The magnitude of the frictional force is calculated through common empirical formulas.

2.1.2. Energy equation

Since thermal non equilibrium is considered between phases, the energy conservation equation for each phase has to be solved. For getting the solid temperature inside the reactor, the energy conservation equation for solid is solved for the whole reactor. The time dependent energy conservation equation for solid can be written as:

$$(1-\varepsilon)\rho_s c_{p_s}\frac{\partial T_s}{\partial t} = (1-\varepsilon)\nabla.\left(\lambda_{s_{eff}}\nabla(T_s)\right) - \dot{q}_{conv} + \dot{q} \qquad (4)$$

where $\lambda_{s_{eff}}$ is the heat conduction coefficient, $\dot{q}$ is the volumetric rate of core heat dissipation, and $\dot{q}_{conv}$ is the heat transferred from the gas to the solid phase. For the gas coolant, the equation is only solved for the flow field in the reactor. The temperature-dependent energy conservation equation is written as

$$\frac{\partial\varepsilon\rho_g h_g}{\partial t} + \nabla.(\varepsilon\rho_g\vec{u}h_g) = \nabla.\left(\varepsilon\lambda_{g_{eff}}\nabla(T_g)\right) + \dot{q}_{conv} \qquad (5)$$

where h_g defines specific enthalpy of the gas, $\lambda_{g_{eff}}$ is the heat conductivity variable of the gas, T_g is the temperature of the gas, and $\dot{q}_{conv}$ is the added temperature to the gas from the solid state. The effective heat conductivity of pebble bed media up to 1600 °C is calculated by Zehner and Schlünder (1972) model and beyond this temperature Robold (1982) model is employed. In the cell model (Zehner and Schlünder Model) described earlier, the radiative heat transport in between two connecting pebbles is considered along with molecular conduction but the radiative heat transport through the gaps between pebbles which goes beyond the connected pebbles is not considered. Since radiation heat transfer increases with increasing temperature, this fraction of heat plays a role at higher temperature. In order to capture this effect, Vortmeyer (1966) arranged the spherical particles in layers and analyzed the heat transfer phenomenon. Therefore, here in this work both Zehner