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Evaluation of compressible flow in spherical fueled reactors using the porous media model

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ABSTRACT

In this study, using porous media approach, the compressible flow within the core of a Pebble Bed Modular Reactor (PBMR) is simulated. This reactor has been composed of coated fuel particles with compressible gas as a coolant and graphite as a moderator and reflector. Containing about 450,000 fuel complexes, the reactor core is considered a porous medium subject to high temperature and high pressure helium flow. The porosity and permeability parameters are calculated and utilized. The coolant compressibility has been introduced as an effective parameter in the thermal–hydraulic analysis. Accordingly, using the ANSYS CFX code, which is capable of simulating compressible flow in porous media, the reactor core is simulated and thermal–hydraulic parameters of the core are obtained through Computational Fluid Dynamic (CFD) approach. The heat flux in the core is first obtained in axial and radial coordinates by MCNP code and is then used in CFD simulation as a semi sine and an algebraic function. The major characteristics of the flow field have been calculated whereby the thermal–hydraulic parameters such as temperature and pressure profiles have been obtained and compared with other data. Comparing the results obtained with other codes and software, the outcomes show that the inclusion of compressibility is reasonable and will lead to a slight difference between the measured and actual temperature, pressure and velocity. In another stage, pressure drop, flow vortices and helium flow lines are explored for two fuel complexes. The empirical formula of pressure drop presented by Kugeler and Schulten is modified and gas density is considered as a function of the core length. Fuel complexes in the reactor core are randomly arranged. However, because Body Center Cubic (BCC) is the closest arrangement to the random distribution, flow parameters are obtained using the BCC arrangement and they are found to deviate very slightly when compared with predictions of other codes.

1. Introduction

Very high temperature reactor (VHTR) has been highlighted as a promising option for the next generation of reactor technology. The basic concept and advancement of the high temperature reactor (HTR) was first proposed by Daniels (1944). The interest in the concept of HTR was substantially revived due to the growing demand for an enhancement of the safety standards of nuclear plants. Currently, the HTRs have been achieving significant attention due to the variety of desired characteristics such as inherent safety, modularity, relatively low cost, short construction time, and being easy to finance. The Pebble Bed Modular Reactor (PBMR) is a high temperature gas cooled reactor that is currently being designed. The latest designed core has a thermal power of 400 MW, and contains an annular pebble bed with a fixed inner reflector. Compared to the older version, when center reflector is added to the core, thermal inertia will be considered and avoids power peaking at the core center. The designed reactor is 11 m tall containing 15,000 coated particles. The fuel design of fissile kernels, which are coated with carbon and silicon carbide layers mixed with graphite, are suitable to reach a very high burn up, and ensure a full confinement of volatile fission products during normal and abnormal situations. Among the characteristics of HTR, the capability of generating high temperature heat source makes them suitable for various cycles of power conversion (Hassan, 2008). The pebbles are used in a multi-pass pebble-recycling scheme; passing the core six times on the average and reaching a target burn up of more than 90 MWD/kg of fuel, approximately. The fuel handling system consists of three fuel-loading positions at the top and three de-fueling tubes at the bottom (Boer et al., 2008). As HTR is a promising concept for the next generation of nuclear power plants, the nuclear community must have readily available analytical tools capable of performing conceptual design studies, industrial calculations, safety analyses for licensing etc. Based on this concept, general-purpose computer codes must be used to analyze the core neutronics, thermal

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hydraulics, fuel depletion study and safety analysis for the HTRs (Briesmeister, 1997).

There have been many studies to calculate and get neutronic and thermal–hydraulic behavior in PBMR in recent years. Reitsma et al. (2006) made the simulation of a PBMR by coupling different neutronic and thermal–hydraulic codes in two transient and steady states. In addition, Dudley et al. (2008) accomplished thermal–hydraulic simulation of this reactor using TINTE, VSOP, and FLOWNEX codes. Boer et al. (2008) performed a complete research on PBMR that contained definition, governing equations, and simulating neutronic, and thermal–hydraulic in two dimension situations.

Another category of computational fluid dynamics (CFD) analysis has focused on the flow-induced local heat transfer which results in generating a local hot spot on the fuel surface as well as in the inner-fuel matrix. In the case of PBMR, the random distribution of the spherical fuel pebbles causes a highly complicated flow regime, which finally results in differences in the degree of local cooling. Such a flow-induced local hot spot analyses in the PBMR core were recently performed by several institutes. Hassan and Yesilyurt (2002) investigated the flow distribution in an aligned pebble geometry consisting of 27 pebble spheres. In addition, Hassan and Yesilyurt (2003) analyzed the local heat transfer due to complexity of the flow distribution in a Body-Centered Cubical (BCC) structure of pebble beds. Lee et al. (2007) considered the effect of gap between pebbles, and compared velocity vector and vortex in two states. More to the point, Hassan (2008) simulated 24 pebbles, used large eddy simulation (LES) of turbulence, and determined pressure drop and velocity vector among pebbles.

In this paper, the gas flow state in the reactor core has been investigated. The ANSYS CFX (ANSYS Inc., 2006) is employed for CFD calculations. The power shape in core is obtained by MCNP code and flow compressibility is studied by CFD method, and their effects on results have been compared with other codes. Considering the results, the experimental formula of pressure drop presented by Kugeler and Schulten is amended, and gas density is considered a function of the core length. Also, in this analysis, a small part of the core containing 24 number of fuel complex have been considered. Using $k-\varepsilon$ model, gas compressible flow is studied. Gas turbulence effects have been considered and velocity vector and vortex, flow direction, flow separation point and pressure drop have been obtained. Because fuel complexes in the reactor core are randomly arranged, in this part, the fuel complexes have been arranged in a Body Center Cubic (BCC) that is the most similar arrangement to the random one. Fluid parameters of helium in compressible mode are obtained through BCC, and they are of much fewer errors when compared with other codes.

2. Brief reactor core description

The proposed PBMR, is a 400 MWt reactor in south Africa, utilizing tristructural isotropic (TRISO) fuel with a vertical steel reactor pressure vessel, 6.2 m in the inner diameter (Chang et al., 2007).The reactor core is composed of an inner graphite moderator surrounded by an annular fuel zone. The fuel zone is surrounded by an annular graphite zone, which is shown in Figs. 1 and 2. The design parameters of the reactor are given in Table 1.

As shown in Fig. 3, pebble fuel contains 15,000 TRISO fuel particles. Fuel particles are presented in a graphite matrix of 0.5 cm diameter, which holds the particles together and acts as a moderator. The uranium dioxide fuel in TRISO particles is surrounded by three layers of pyrolitic carbon (PyC) and a layer of silicon carbide (Acir et al., 2011).

3. Analyzing the flow model and simulating the reactor core

3.1. Porous media

Regarding this reactor physics, geometries such as pack beds or parallel tubes could be assumed as porous media. There are several equations to calculate the porosity, tortuosity, permeability and other parameters of porous media. This reactor, which has about 450,000 packed fuel beds over which helium goes, is assumed as a porous medium. The main characteristics of every porous medium are porosity and permeability that are being explained for this core geometry.

3.1.1. Porosity

The volume fraction occupied by void is called the porosity in porous media. The porosity in this geometry is 0.39 and the packed

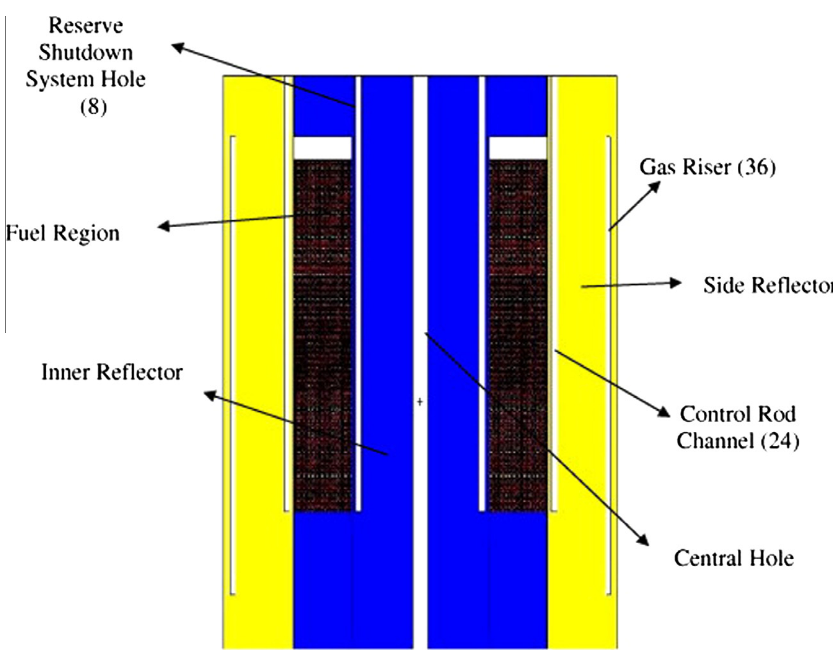

Fig. 1. PBMR-400 core layout (Acir et al., 2011).