Comparison of 2D and 3D heat transfer models around the coolant channels in the HTR-PM side reflector

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A B S T R A C T

In the HTR-PM pebble bed reactor heat is produced in a cylindrical core surrounded by a graphite reflector. The helium coolant flowing down through the core first flows up through 3D coolant channels in the reflector, cooling it. Heat is also transferred through the reflector in radial direction to the pressure vessel and other surroundings, which is the main heat loss mechanism during a loss of cooling accident. Usually heat transfer in the reflector region is modelled using a 2D axi-symmetric geometry, modelling the region containing the coolant channels as a homogenized mixture of coolant channel and graphite reflector using a porosity value, sometimes using very coarse meshes. In reality temperature gradients in azimuthal direction will exist around the coolant channels, possibly affecting both heat transfer to the coolant and heat transfer through the graphite around the coolant channels to the outer boundary. This paper investigates the accuracy of the 2D model by comparing calculations for a fine and course 2D mesh with a 3D mesh in which the coolant channel geometry is explicitly modelled. Two cases were investigated: one representing full power operation, and the other a loss of forced cooling incident with no helium flow through the coolant channels. The course 2D mesh resulted in large errors in the reflector temperature field for full power conditions, overestimating the temperature drop across the coolant channel region. The 3D fine mesh compared reasonably well with the 3D mesh, although it resulted in both an overestimation of the effective heat transfer rate to the coolant channels and an underestimation of the effective resistance to heat transfer in the reflector in the radial direction around the coolant channels. Especially the last can lead to an underestimation of reflector and core temperatures during a loss of coolant accident. To amend this problem, the conductivity of the graphite in the coolant channel region should be adjusted in the 2D porous model to compensate for the added effective resistance to heat transfer in radial direction due to the geometry.

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1. Introduction

The pebble bed nuclear reactor, a high temperature gas cooled reactor design, is one of the main candidates for next generation nuclear power plants (IAEA, 2001a). Key features include the passive safety of the reactor, higher thermal efficiency due to higher coolant outlet temperatures, and the possibility of on-line refuelling by extracting pebbles at the bottom of the bed and adding pebbles to the top. In these reactors, the fuel is contained within graphite spheres, which form a randomly packed bed in a cylindrical core cavity surrounded by a graphite reflector. The helium coolant first flows upwards through coolant channels in the graphite reflector, and then via a plenum downwards through the pebble bed, removing the fission heat. Heat is also transferred from the pebble bed to the graphite reflector, which is cooled by the cold helium flowing upward through the coolant channels. These coolant channels are arranged in a ring in the reflector at equidistant positions. Finally, heat is transferred through the reflector and via various core components to the outside, which is the main heat loss mechanism during a loss of cooling accident.

In pebble bed calculations often 2D r–z models are used, as in many cases the use of 3D models is too computationally expensive. In these models the ring of coolant channels is modelled as a homogenized zone in the reflector, using a porosity to represent the fractional volume occupied by the coolant channels (Zheng et al., 2009). Especially for system analysis purposes the meshes for these models are often quite coarse, using only a few or even one mesh cell for the coolant channel region in the reflector. This brings us to the question how accurate these models are in calculating the heat transfer through the reflector to the coolant channels and around the channels to the outside.

To this end we compared results for heat transfer calculations using three different meshes for the reflector. The first two are 2D meshes using r–z coordinates and a homogenized coolant channel region, with one mesh (2D1) using only one mesh cell in the coolant channel region, and the other mesh (2Dfine) using a fine mesh in this region. The third mesh is a 3D model of a 12° wedge around one coolant channel, making use of the symmetry of the coolant channels in the reflector.

Heat transfer calculations were performed with pebFoam, which is described in the next section. A simplified geometric model of the Chinese High Temperature gas-cooled Reactor-Pebble-bed Module (HTR-PM) (Zhang et al., 2009) was used, for which two separate cases were considered. In the first case, detailed in Section 3, the temperature distribution in the graphite reflector is calculated.