Nuclear Engineering and Design 256 (2013) 264–273

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Development of three-dimensional hot pool model in a system analysis code for pool-type FBR

Danting Sui [a,*], Daogang Lu [a], Lixia Ren [b], Yizhe Liu [b]

[a] School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China
[b] China Institute of Atomic Energy, Beijing 102413, China

HIGHLIGHTS

- ► A 3-D hot pool analysis code with porous medium model was developed.
- ► The coupling between 3-D model and system analysis code was finished.
- ► The coupled code was used to analyze T-H behavior in upper plenum of MONJU.
- ► Complex flow field in CEFR hot pool was analyzed with the coupled code.

ARTICLE INFO

Article history:
Received 6 January 2012
Received in revised form 24 July 2012
Accepted 1 August 2012

ABSTRACT

A three-dimensional hot pool analysis code with SIMPLE algorithm was developed based on staggered grid, which can predict thermal-hydraulic characteristic in hot pool of pool-type liquid metal fast breeder reactor (LMFBR) under Cartesian and cylindrical coordinate systems. After being incorporated into system analysis code for pool-type fast reactor in China (SAC-CFR), the coupled code was used to analyze the thermal-hydraulic behavior in the upper plenum of fast breeder reactor “MONJU” during reactor scram transient. A basic agreement was obtained, which means the present model is effective. And then the coupled code with newly developed porous medium model was used to analyze the flow field in China Experimental Fast Reactor hot pool under steady-state operation condition. The distribution characteristic of flow field in hot pool showed the effectiveness of porous medium model, which formed preparations for further development of passive residual heat removal system in-vessel.

1. Introduction

The sodium in pool-type liquid metal fast reactor provides vital function of removing reactor generated heat. Accurate prediction of coolant thermal-hydraulic characteristic in hot pool cannot only evaluate the performance of key component in hot pool properly, but also improve the system analysis ability through more accurate intermediate heat exchanger (IHX) inlet temperature. In advanced FBR, the directly in-vessel decay heat remove system (DIDHRS) is being considered to be used to improve inherent safety, which makes it impossible to analyze the complicated phenomenon caused by DIDHRS with traditional 1D or 2D system analysis code. Therefore, the coupling of system code and 3D thermal-hydraulic analysis code is always an important challenge to take into account local 3D effects on global system behavior. Considering that the hot pool is arranged with more complex key components and filled with higher-temperature coolant than cold pool, 3D thermal-hydraulic characteristic in hot pool is a research focus in this study.

Many researches on thermal-hydraulic characteristic in hot pool have been carried out currently in some countries and organizations. In the aspect of experiment, many kinds of in and out of core experiment have been performed for their specified research purpose in America, France, Japan, Russia, etc. (Hofmann and Essig, 1993; Kasinathan, 1993; Ieda, 1993). In the aspect of theory, besides the commercial computational fluid dynamics software such as CFX, FLUENT, many three-dimensional thermal-hydraulic analysis codes have been specially developed for evaluating the thermal-hydraulic performance in fast reactor, such as COMMIX (Chien et al., 1993) series developed by ANL, AQUA (Muramastsu et al., 1987) developed in PNC, TRIO_U (Tenchine et al., 2012)in France, FASTOR-3D (Degui et al., 1998) and DHRSC (Yishao et al., 1991) in China. During transient analysis, all these analysis codes can only predict the thermal-hydraulic performance in particular component such as hot pool at a certain boundary condition. As to the coupling of system code and 3D analysis code, many researches have been performed by organizations and researchers. For instance in Europe,

* Corresponding author. Tel.: +86 10 51963824; fax: +86 10 51963351.
E-mail addresses: suidanting@163.com (D. Sui), ludaogang@ncepu.edu.cn (D. Lu), lixia.ren@gmail.com (L. Ren), ramzi@sina.com (Y. Liu).

0029-5493/$ – see front matter
http://dx.doi.org/10.1016/j.nucengdes.2012.08.032

the Trio_U has been coupled to CATHARE by NURISP (Emonot et al., 2012) and THINS (Xu et al., 2010) teams, and the related application, verification and validation are in progress. Also, the coupling used for PWR is also a research focus in recent years. In Japan, two-dimensional upper plenum model was incorporated into a one-dimensional system analysis code named SSC-L (Mochizuki, 2007, 2010).

From the aspect of fast reactor sustainable development in China, it is the only choice to develop system analysis code and 3D analysis code specialized for CEFR and next generation demonstration fast reactor.

In the present study, a three-dimensional hot pool analysis code with SIMPLE algorithm was developed based on staggered grid under Cartesian and cylindrical coordinate systems. After being incorporated into System Analysis Code for China Fast Reactor (SAC-CFR), the coupled code was used to analyze the thermal-hydraulic characteristic in upper plenum of MONJU during the scram transient starting from 45% thermal power operation. And then the coupled code with newly incorporated porous medium model was used to analyze the flow field in China Experimental Fast Reactor (CEFR) hot pool under steady-state operation condition.

2. Governing equations and discretization

The general form of governing equations in Cartesian and cylindrical coordinate systems can be written as the following:

$$\frac{\partial \rho\phi}{\partial t} + \frac{1}{r}\frac{\partial (rJ_x)}{\partial x} + \frac{1}{r}\frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z} = S_\phi \tag{1}$$

$$J_x = \rho u\phi - \Gamma_\phi \frac{\partial \phi}{\partial x}$$

$$J_y = \rho v\phi - \Gamma_\phi \left(\frac{1}{r}\frac{\partial \phi}{\partial y}\right)$$

$$J_z = \rho w\phi - \Gamma_\phi \frac{\partial \phi}{\partial z}$$

Value of r is 1 for Cartesian coordinate and remains as r for cylindrical coordinate.

For the continuity equation, momentum equation and energy equation, ϕ represents 1, u, v, w, and h respectively. For Cartesian coordinate, three directions are denoted as x, y and z. For cylindrical coordinate, three directions are denoted as r, θ and z. The source terms in Cartesian and cylindrical coordinate are:

$$S = \begin{pmatrix} 0 \\ -\dfrac{\partial p}{\partial x} + \rho g_x \\ -\dfrac{\partial p}{\partial y} + \rho g_y \\ -\dfrac{\partial p}{\partial z} - \rho g_z \\ Q \end{pmatrix}, \qquad S = \begin{pmatrix} 0 \\ -\dfrac{\partial p}{\partial r} + \dfrac{\rho v^2}{r} - \dfrac{2\mu}{r^2}\cdot\dfrac{\partial v}{\partial \theta} - \dfrac{\mu u}{r^2} \\ -\dfrac{1}{r}\dfrac{\partial p}{\partial \theta} - \dfrac{\rho uv}{r} - \mu\dfrac{v}{r} + \dfrac{2\mu}{r^2}\cdot\dfrac{\partial v_r}{\partial \theta} \\ -\rho g - \dfrac{\partial p}{\partial z} \\ Q \end{pmatrix}$$

The conservation equations incorporating porous medium formulation are based on averaging local volume. The averaging local volume is similarly defined as those in continuum medium, and provides spatially smoothed equations solved with the general solution method. After incorporating porous medium model, the governing equations can be written as:

$$\gamma_V \frac{\partial \rho\phi}{\partial t} + \frac{1}{r}\frac{\partial (r\gamma_x J_x)}{\partial x} + \frac{1}{r}\frac{\partial (\gamma_y J_y)}{\partial y} + \frac{\partial (\gamma_z J_z)}{\partial z} = S_\phi \tag{2}$$

J_x, J_y and J_z have the same expressions with previous ones.

Specially, volume porosity γ_V can be defined as:

$$\gamma_V = \frac{V_f}{V} \tag{3}$$

and directional surface porosity γ_x, γ_y and γ_z can be expressed as:

$$\gamma_i = \frac{A_f}{A}, \quad \text{where} \quad i = x,\ y,\ z \tag{4}$$

Volume porosity is defined as the ratio of the volume occupied by fluid in a control volume V_f to the total control volume V. The directional surface porosity is similarly defined as the ratio of the area available A_f for fluid flow through a control surface to the total control surface area A.

It should be noted that volume porosity and directional surface porosity are used to model the flow space reduction for the presence of solid structure. Distributed heat source and distributed resistance are used to model the effect of the presence of solid structure on momentum and energy exchange, which are classified into the source terms.

The finite volume method based on staggered grid is chosen as the discretization method. The discretized equations are derived by integrating the governing equations over a control volume. The power-law scheme was used to construct the discretized equation. The power-law expressions for a_E can be written as (Patankar, 1980):

$$\frac{a_E}{D_e} = \begin{cases} 0, & P_{\Delta e} > 10 \\ (1 - 0.1P_{\Delta e})^5, & 0 \le P_{\Delta e} \le 10 \\ (1 + 0.1P_{\Delta e})^5 - P_{\Delta e}, & -10 \le P_{\Delta e} \le 0 \\ -P_{\Delta e}, & P_{\Delta e} < -10 \end{cases} \tag{5}$$

a_E is the neighboring coefficient, representing the convective and diffusion effect from the neighboring node. $P_{\Delta e}$ is defined as the ratio of convective mass flux to diffusion conductance at cell faces.

$$P_{\Delta e} = \frac{F_e}{D_e} = \frac{\rho u \delta x_e}{\eta_e} \tag{6}$$

$$F_e = (\rho u)_e \times A_e \tag{7}$$

$$D_e = \frac{\eta_e \times A_e}{(\delta x)_e} \tag{8}$$

where F_e indicates the strength of convection, while D_e is the diffusion conductance. ρ, u, η_e and A_e is the density, velocity, dynamic viscosity and flow area of control volume respectively. It should be noted that, whereas D always remains positive, F could take either positive of negative values depending on the direction of flow.

Take the cylindrical coordinate system for example to perform the discretization of governing equation. The discretized form of momentum equations in three directions obtained through the conservation of total flux over a control volume can be written as:

$$a_P\varphi_P = a_E\varphi_E + a_W\varphi_W + a_N\varphi_N + a_S\varphi_S + a_T\varphi_T + a_B\varphi_B + b \tag{9}$$

The expressions of b in three directions are:

For the radial direction,

$$b = SU_1 + SU_2 - (p_P - p_W)r\Delta\varphi\Delta z + \frac{\rho u_0}{\Delta t}\Delta V \tag{10}$$

$$SU_1 = \frac{1}{16}\rho\Delta r\varphi\Delta z[v(i,j,k) + v(i,j+1,k) + v(i-1,j,k) + v(i-1,j+1,k)]^2$$

$$SU_2 = -\frac{\eta}{r}\Delta r\Delta z\,[v(i,j+1,k) + v(i-1,j+1,k) - v(i,j,k) - v(i-1,j,k)]$$

For the axial direction,

$$b = -(p_P - p_B)r\Delta r\Delta\varphi + \frac{\rho w_0}{\Delta t}\Delta V + \rho g\Delta V \tag{11}$$