Thermal Hydraulic Analysis of Liquid Metal Reactor Subchannel

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1. Introduction

Thermal hydraulic design of a liquid metal reactor (LMR) must conform to a set of design criteria. They are typically related to the fuel, cladding, and sodium outlet temperatures under various operating conditions. Detailed core-wide temperature calculations are consequently needed to ensure that the design bases are satisfied. A fast-running thermal hydraulic code is necessary for repeated detailed core-wide temperature calculations. However, it requires a large amount of computation time to solve the flow governing equations for every channel in a core using the conventional subchannel analysis model.

This work investigates the coolant temperatures in a 16 bare rod square lattice of an LMR core based on the ENERGY model. The effect of the wire-wrap was not accounted for.

2. Thermal Analysis

2.1 ENERGY Model

The subchannel analysis method is commonly used in thermal hydraulic analysis of a wire-wrapped LMR rod bundle. A bulk average value characterizes each of the thermohydrodynamic conditions in the axial control volume of each subchannel.

In order to enhance the computational efficiency, the simplified energy equation with mixing model called ENERGY was developed in 1970s specifically for the LMRs. The simplicity of the model results from the replacement of the exact momentum coupling between channels with approximations appropriate for wire-wrapped rod assemblies. ENERGY mainly deals with the temperature distribution for the forced convection problems with accuracy comparable to that of a detailed subchannel analysis model in much shorter computing time [1].

Conventional LMR subchannels are triangular with wire-wrapped rods. However, in this study, we consider a rectangular subchannel assembly illustrated in Fig. 1. There are two reasons to perform a numerical analysis with a rectangular subchannel. First, it is common to adopt a rectangular assembly for a small LMR having thermal power less than 100 MW. Our reference is made to the Battery Omnibus Reactor Integral System (BORIS) having 22.5 MW thermal power [2]. Second, it is easy to analyze the rectangular assembly that is geometrically simpler than triangular subchannels.

The derivation of the model starts by dividing the rod array of an LMR assembly into two predominant regions: the central and wall regions as shown in Fig. 1, and by assuming characteristic flows in each region. The central region includes the interior subchannels, while the wall region includes the edge and corner subchannels.

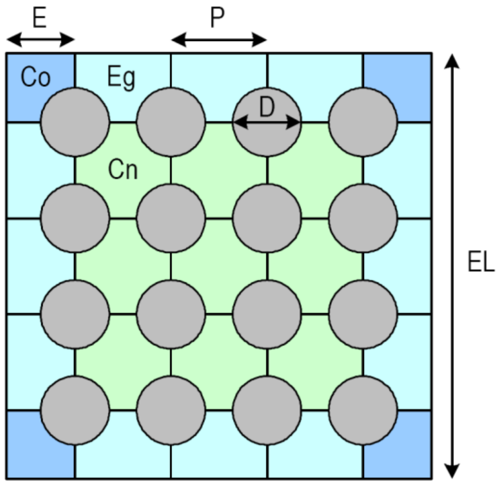

Fig. 1. Geometry of a 16-rod square lattice LMR core.

The resulting energy equation for subchannels in the central region is

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + Q \qquad (1)$$

where T, ρ, Cp, k, and Q denote the temperature, density, specific heat, thermal conductivity and volumetric heat generation in the coolant, respectively.

The four parameters in the energy equation can be obtained from experimentally determined correlations [3]. For a particular total flow rate, the two axial velocities in the central and wall regions are obtained from the flow split correlations determined by the hydraulic diameter flow analysis and experimental data [1].

The flow split parameters are derived by assuming that the friction factor for each channel i can be approximated by a simple function of the Reynolds number Re_i as

$$f_i = C_{fi} Re_i^{-m} \qquad (2)$$

Using the continuity and the equal pressure drop boundary condition, the flow velocity split is obtained as a function of subchannel equivalent diameters and the friction factor constants C_{fi} and an exponent. The final flow split correlations depend on how to correlate the friction factor constants and exponent.

2.2 Numerical Formulation and Solution Schemes

Each of these assemblies is discretized axially using the standard subchannel layout based on the number of rods to numerically solve for Eq. (1). The interior region of the duct wall is divided into interior, edge, and corner subchannels in Fig. 1. The heat balance equation for each axial segment of these subchannels is obtained by integrating the corresponding energy equation over the axial control volume and by approximating the temperature gradients at the lateral surfaces using a finite difference scheme in Fig. 2.

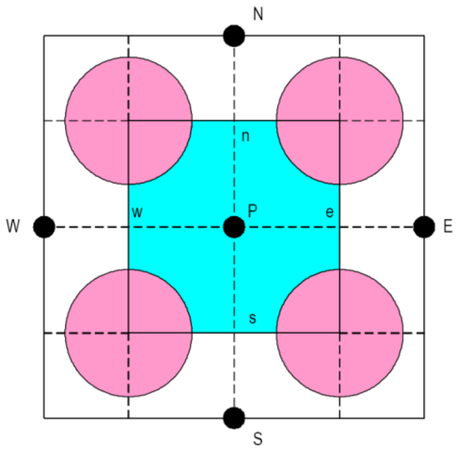

Fig. 2. A finite difference scheme of a rectangular subchannel.

As a result of these approximations, a typical heat balance equation for a control volume is

$$a_P T_P = a_E T_E + a_W T_W + a_N T_N + a_S T_S + b \qquad (3)$$

where T_p, T_E, T_W, T_E and T_S are the temperature of the node of interest shown in Fig. 2, and a_p, a_E, a_W, a_E and a_S are coefficients depending upon the coolant thermal conductivity and subchannel centroid distances [4].

Implicit differencing of the energy equation results in a linear system for every radial plane. Since the overall solution for a three-dimensional problem proceeds by marching upward after solving the linear system for each plane, the linear system is to be solved repeatedly. An efficient linear system solver thus is desired. An iterative solver is an obvious choice here because the linear system is very sparse. The Gauss-Seidel method was chosen as the iterative solver.

3. Numerical Results

The above computational method is applied to MATLAB for predicting the steady-state temperature field in an LMR core. The assembly pitch, edge and height are 0.038 m, 0.015 m, and 3 m, respectively. The fuel power density is $6.16788 \times 10^7\, {}^{W}/_{m^3}$. The mass flow rate is 100 kg/s, and the inlet temperature is 440℃.

Table I lists the outlet temperature distribution in the 16 rod square lattice LMR core. The number of iterations is 100.

The average outlet temperature and the average outlet temperature rise for the square lattice LMR are 608.6℃ and 168.6℃, respectively. The average temperature rise for BORIS was 123.45℃.

Table I: Oultet Temperature Distribution in 16 Rod Square Lattice LMR Core (℃)

574.6373	599.0776	591.2412	599.8424	576.7655
595.8410	615.0385	617.9536	629.5253	617.6544
597.9359	615.7036	614.8723	618.2861	613.5311
609.3303	617.0115	625.5572	617.2886	610.8377
576.0672	599.4323	592.0946	599.4655	576.2113

4. Summary

Thermal analysis has been made of the square array subchannel. There is temperature difference in the result. So as to improve the accuracy of the thermal analysis for the LMR core, an account must be taken of the eddy flow in the wall region.

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