Dimensional Study on Pressure Matrix for THALES

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1. Introduction

KEPCO NF has developed the core thermal hydraulic design code, THALES (Thermal Hydraulic AnaLyzer for Enhanced Simulation of core). This paper presents the derivation and characteristics of pressure matrix for three dimensional geometry at governing equation of the code. This work was done to check the calculation efficiency for small number channel problem as CETOP.

2. Code Descriptions and Characteristics

2.1 Matrix of Two Dimensional Geometry for Governing Equations

THALES code is based on two dimensional subchannel geometry of the fuel assemblies, which uses the governing equations of mass, axial momentum, lateral momentum, and energy as follows:

$$A\frac{\partial\rho}{\partial t}+\frac{\partial m}{\partial z}+\sum e_{ij}w=0 \tag{1}$$

$$\begin{aligned}&\frac{\partial m}{\partial t}+\frac{\partial}{\partial z}\left(\frac{v'}{A}m^2\right)+\sum e_{ij}wu^*=-A\frac{\partial p}{\partial z}\\&-\frac{1}{2}\left(\frac{f\phi^2 v_f}{D_h}+\frac{K_{SG}}{\Delta z}v'\right)\frac{m^2}{A}-Ag\rho-c_T\sum w'\Delta U\end{aligned} \tag{2}$$

$$\frac{\partial w}{\partial t}+\frac{\partial w\bar{u}}{\partial z}=\frac{s}{l}\left(p_i-p_j\right)-\frac{1}{2l}K_G v'^*|w|\frac{w}{s} \tag{3}$$

$$\begin{aligned}&A\left(\rho\frac{\partial h}{\partial t}-h_{fg}\frac{\partial\psi}{\partial t}\right)+m\frac{\partial h}{\partial z}+\sum e_{ij}w\left(h^*-h\right)\\&+\frac{1}{\Pr_t}\sum e_{ij}w'\Delta h=q'\end{aligned} \tag{4}$$

The above equations are coupled to calculate the pressure distribution at each axial position. The resulting pressure equation is as follows;

$$\begin{aligned}&(DP/DX)_j-\left(\frac{S}{\ell}\right)\Delta X_j^2 g_c\sum\{C\}\left[(DP/DX_J)_{ii}-(DP/DX_J)_{jj}\right]\\&+\sum\{C\}\left(\frac{S}{\ell}\right)g_c\Delta X_j\left(P_{ii}-P_{jj}\right)_j=M-\sum\{C\}\left[w_J^n\frac{\Delta X_J}{\Delta t}+\left(\frac{\overline{mv'}}{A}\right)_{J-1}w_{J-1}\right]\end{aligned} \tag{5}$$

2.2 Matrix of Three Dimensional Geometry for Governing Equations

In order to calculate all pressure field with a matrix, the pressure equation has to be modified. The pressures between two axial positions are coupled to the following equation.

$$\left(P_{ii}-P_{jj}\right)_J=\left(P_{ii}-P_{jj}\right)_{J+1}-\Delta X_{J+1}\left[(DP/DX_{J+1})_{ii}-(DP/DX_{J+1})_{jj}\right] \tag{6}$$

Inserting Eq (6) into Eq (5), new pressure equation is constructed as follows;

For $1<J<N$

$$\begin{aligned}&(DP/DX)_J-\left(\frac{S}{\ell}\right)_J\Delta X_J^2 g_c\sum\{C\}_J\left[(DP/DX_J)_{ii}-(DP/DX_J)_{jj}\right]\\&-\left(\frac{S}{\ell}\right)_J g_c\Delta X_J\Delta X_{J+1}\sum\{C\}_J\left[(DP/DX_{J+1})_{ii}-(DP/DX_{J+1})_{jj}\right]\\&-\left(\frac{S}{\ell}\right)_J g_c\Delta X_J\Delta X_{J+2}\sum\{C\}_J\left[(DP/DX_{J+2})_{ii}-(DP/DX_{J+2})_{jj}\right]\\&-\left(\frac{S}{\ell}\right)_J g_c\Delta X_J\Delta X_{J+3}\sum\{C\}_J\left[(DP/DX_{J+3})_{ii}-(DP/DX_{J+3})_{jj}\right]\\&\cdots\\&-\left(\frac{S}{\ell}\right)_J g_c\Delta X_J\Delta X_N\sum\{C\}_N\left[(DP/DX_N)_{ii}-(DP/DX_N)_{jj}\right]\\&=M_J-\sum\{C\}_J\left[w_J^n\frac{\Delta X_J}{\Delta t}+\left(\frac{\overline{mv'}}{A}\right)_{J-1}w_{J-1}+\left(\frac{S}{\ell}\right)_J g_c\Delta X_J\left(P_{ii}-P_{jj}\right)_N\right]\end{aligned} \tag{7}$$

For $J=N$

$$\begin{aligned}&(DP/DX)_N-\left(\frac{S}{\ell}\right)_N\Delta X_N^2 g_c\sum\{C\}_N\left[(DP/DX_N)_{ii}-(DP/DX_N)_{jj}\right]\\&=M_N-\sum\{C\}_N\left[w_N^n\frac{\Delta X_N}{\Delta t}+\left(\frac{\overline{mv'}}{A}\right)_{N-1}w_{N-1}+\left(\frac{S}{\ell}\right)_N g_c\Delta X_N\left(P_{ii}-P_{jj}\right)_N\right]\end{aligned} \tag{8}$$

The above pressure equations can be represented as the following matrix to be solved.

$$\begin{bmatrix}1-\sum^{NI}\alpha_{12}^1 & \cdots & 0 & -\sum^{NI}\alpha_{12}^2 & \cdots & 0 & \cdots & -\sum^{NI}\alpha_{12}^3 & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & \cdots & 1-\sum^{NI}\alpha_{NC2}^1 & 0 & \cdots & -\sum^{NI}\alpha_{NC2}^2 & \cdots & 0 & \cdots & -\sum^{NI}\alpha_{NC2}^3\\ 0 & 0 & 0 & 1-\sum^{NI}\alpha_{13}^1 & \cdots & 0 & \cdots & -\sum^{NI}\alpha_{13}^2 & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & 0 & 0 & 0 & \cdots & 1-\sum^{NI}\alpha_{NC3}^1 & \cdots & 0 & \cdots & -\sum^{NI}\alpha_{NC3}^2\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-\sum^{NI}\alpha_{NCNJ1}^1 & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 1-\sum^{NI}\alpha_{NCNJ1}^1\end{bmatrix}\begin{bmatrix}\left.\frac{dp}{dx}\right|_{12}\\ \vdots\\ \left.\frac{dp}{dx}\right|_{NC2}\\ \left.\frac{dp}{dx}\right|_{13}\\ \vdots\\ \left.\frac{dp}{dx}\right|_{NC3}\\ \vdots\\ \left.\frac{dp}{dx}\right|_{1NJ1}\\ \vdots\\ \left.\frac{dp}{dx}\right|_{NCNJ1}\end{bmatrix}=\begin{bmatrix}B_{12}\\ \vdots\\ B_{NC2}\\ B_{13}\\ \vdots\\ B_{NC3}\\ \vdots\\ B_{1NJ1}\\ \vdots\\ B_{NCNJ1}\end{bmatrix}$$

2.3 Numerical Method

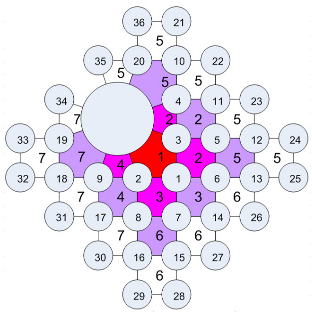
The matrix for governing equation is solved with the preconditioned bi-conjugate gradient method (PBCGM) or Gauss Elimination method. The characteristics of THALES are as follows;

Table 1. Characteristics of THALES code

	THALES
Flow solution	*dp/dx*
Mesh (Axial node)	Non-staggered
Energy eq. matrix	Used
Matrix solver	PBCGM, Gauss elimination
Steam table	ASME,NIST
Precision	Double

2.4 Results

The example calculation was performed for the small number channel problem as follows;



$$\begin{bmatrix} 1 & 2 & 3 & 4 & 0 & 0 & 0 & 0 \\ 1 & 2 & 3 & 0 & 5 & 0 & 0 & 0 \\ 1 & 2 & 3 & 4 & 0 & 6 & 0 & 0 \\ 1 & 0 & 3 & 4 & 0 & 0 & 7 & 0 \\ 0 & 2 & 0 & 0 & 5 & 6 & 0 & 8 \\ 0 & 0 & 3 & 0 & 5 & 6 & 7 & 8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 7 & 8 \\ 0 & 0 & 0 & 0 & 5 & 6 & 0 & 8 \end{bmatrix}$$

Figure 1. Schematic of channel connections

Matrix size

At the present problem, number of channels is 8 and axial node number is 51. Thus, the matrix size for the two dimensional section at each axial position is 8x8.

But, the matrix size for the three dimensional volume becomes very large, which is 408 x 408. Because of that, if the channel number becomes very large, the matrix size of the governing equation becomes enormous.

If number of channel is 48 and number of axial node is 41, nonzero element is 208 at each axial section. For all regions, it becomes 8320. But, for matrix of three dimensional geometry, matrix size becomes 1920x1920. Nonzero element is 170560. It results to the lack of computer memory. Therefore, for large number channel problem, this method is not practical.

Calculation time

The above case was performed at a PC. The calculation time is as follows;

	PBCGM	Gauss Elimination
2D matrix	0.093 sec	0.094 sec
3D matrix	1.344 sec	11.187 sec

Because of the matrix size, the calculation time of three dimensional matrix solver becomes more longer.

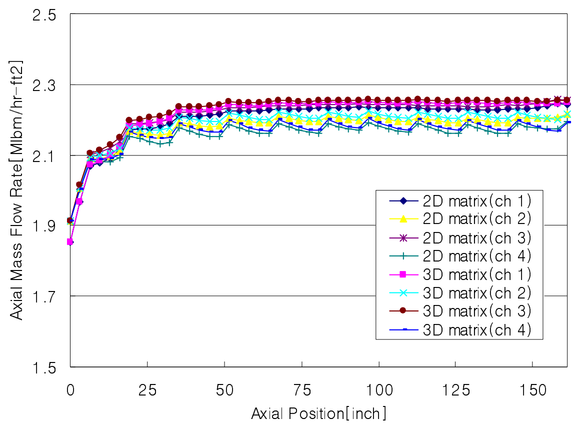


Figure 2 Comparison of the results between 2D and 3D matrix

Therefore, three dimensional matrix is possible for the small number channel problem.

3. Conclusions

KEPCO NF has developed THALES code for the application to the core thermal hydraulic design. The code was tested for matrix of two dimensional geometry and three dimensional geometry. Two results are the same within error criterion. For the three dimensional matrix, the coefficient matrix size becomes very large for large number channel problem. It makes that long calculation time is required. Three dimensional matrix solver is applicable to small number channel problem. Generally, for hydraulic analysis of the reactor core, two dimensional approach is more efficient than three dimensional matrix solver.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

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