Analysis Methodology of Reactor Vessel Internal Flow using Flow Network Model

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1. Introduction

Flow distribution inside the reactor vessel is of interest to engineers who design nuclear reactors and the reactor coolant system (RCS). It is very important to look into how the coolant flows inside the reactor vessel. Besides, the data can be used to yield additional design data required for subsequent works, e.g. safety analysis and hydraulic load analysis. Although the computational fluid dynamics can be considered as one way to analyze the reactor vessel internal flow, it still has many problems that need to be resolved (e.g. computational time and cost, and verification of results).

In this study, the analysis methodology of the reactor vessel internal flow using a flow network model is introduced. A new program called VESPER was developed and the program will supersede an existing program. The program employs the gradient method [1] for the flow network analysis. This study includes the information on the newly developed program (e.g. analysis method of the program), and shows the analysis results for the current OPR1000 flow network and a transformed network.

2. Methods and Results

2.1 Program Development

VESPER is a flow network analysis program which is developed in order to improve convergence, accuracy and user convenience. The flow network analysis for OPR1000 reactor design was performed by using a program, NOTTINGHAM, developed by Combustion Engineering, Inc. This program was necessary to be substituted because of the license agreement. Although there are various commercial programs, it is required to develop a program which is convenient to use and prevents probable human errors from occurring during pre- or post-processing of data.

VESPER employs the gradient method to solve flow networks. There are several methods as well as the gradient method, such as Hardy Cross method [2], Newton-Raphson method [3], linear method [4,5]. In general, flow network analysis methods have convergence difficulties due to branches with a relatively low resistance and poor initial nodal heads [5,6]. However the gradient method has advantages to resolve problems with poor initial values and relatively low resistance branches. Moreover, this method uses a simple set of input data without closed or pseudo loop information.

The energy equation for each branch and the continuity equation for each node are solved by the gradient method. The system of equations is as follows:

$$RQ^2 + H_{out} - H_{in} = 0 \quad \text{at each branch}$$
$$\sum Q_{in} - \sum Q_{out} = 0 \quad \text{at each node}$$

where R and Q are an overall resistance and a mass flow rate at each branch, respectively. H_{in} and H_{out} are heads at upstream and downstream nodes of each branch, that is to say a nodal head. Q_{in} and Q_{out} represent inflows and outflows at each node, respectively. The number of the equations is the same as the sum of the numbers of branches and nodes.

To solve the system of equations, the Newton-Raphson method is applied to both of the head and flow rate. It leads to the following equations:

$$\mathrm{nA}_{11}\Delta Q^{(m)} + \mathrm{A}_{12}\Delta H^{(m)} = -dE^{(m-1)}$$
$$\mathrm{A}_{21}\Delta Q^{(m)} = -dq^{(m-1)}$$

where n is a constant, 2. The matrix A_{11} is a diagonal matrix.

$$\mathrm{A}_{11} = \begin{bmatrix} R_1|Q_1|^{n-1} & \cdots & 0 \\ \vdots & R_i|Q_i|^{n-1} & \vdots \\ 0 & \cdots & R_{ib}|Q_{ib}|^{n-1} \end{bmatrix}$$

where R_i is an overall resistance of i branch. Q_i is a known flow rate at i branch. The subscript ib is the number of branches. The matrices A_{12} and A_{21} consist of the elements of -1, 0 and 1. The elements of A_{12} are identical to the coefficients of each nodal head term in the energy equation, which are partial derivatives of the left-hand side of the equation with respect to the nodal heads. The elements of A_{21} are obtained as partial derivatives of the left-hand side of the continuity equation with respect to the mass flow rates. The matrices meet the following relationship:

$$(\mathrm{A}_{12})_{ij} = (\mathrm{A}_{21})_{ji}.$$

dE and dq are the left-hand sides of the energy and the continuity equations, respectively. (m) and $(m-1)$ stand for iteration steps. Thus $dE^{(m-1)}$ and $dq^{(m-1)}$ are known values at (m) iteration step. Gauss elimination is used to calculate $\Delta Q^{(m)}$ and $\Delta H^{(m)}$ of the equations. Finally the flow rates and nodal heads at (m) iteration step are obtained as follows:

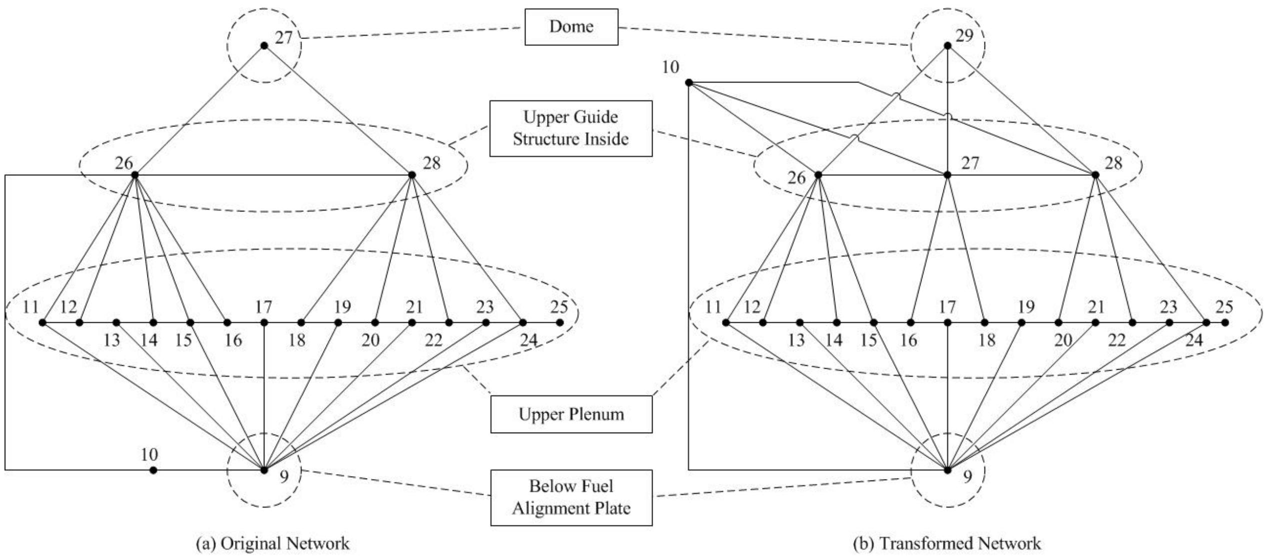

Fig. 1. Upper guide structure and dome flow networks

$$Q^{(m)} = Q^{(m-1)} + \Delta Q^{(m)}$$
$$H^{(m)} = H^{(m-1)} + \Delta H^{(m)}$$

The accuracy of this program was checked through a simple example in a textbook [7].

2.2 Reactor Vessel Internal Flow Network

The reactor vessel internal flow network consists of paths of the main, core bypass and leakage flows. The main flow path is a flow path through the inlets, downcomer, lower plenum, core and upper plenum into outlets. The core bypass flow paths are composed of flow paths through the alignment keys, outlet nozzle gaps, core shroud annulus, and guide tubes for the in-core instrumentations and control element assemblies. The leakage flows mean flow paths into the upper guide structure and dome regions which consist of flow paths through the alignment keys, control element guide tubes and upper guide structure support plate flow holes.

Two flow networks were analyzed on a trial basis by VESPER. One is an original network which had been applied to OPR1000 reactors, and the other is a transformed network from the original one. The transformed network has a different network for the upper guide structure and dome region compared to the original. The network configuration other than that of the upper guide structure and dome region is same in two networks. Fig. 1 shows the flow networks of the upper guide structure and dome region.

The major difference between the two networks is the number of nodes corresponding to the upper guide structure inside. Thus, connections of the nodes to the dome and upper plenum are changed and the horizontal connection of the nodes is also changed from one branch to two branches. In the original network, the resistance of one horizontal branch (Fig. 1 (a) Nodes 26 to 28) was defined as those of one web and two cylinder walls of the inner barrel assembly. However it seems to be less resistant because the inner barrel assembly could be divided into three regions by two web rows. The low resistance makes it possible to overpredict flow rate inside the upper guide structure.

On the other hand, in the transformed network, there are three branches indicating flows through the control element guide tube. An actual OPR1000 reactor has the control element guide tubes almost uniformly arranged all around the upper plenum. This network transformation makes the horizontal flow inside the upper guide structure decrease.

2.3 Resistance

The overall resistance R in section 2.1 is determined according to the following head loss:

$$h_{LOSS} = K\frac{V^2}{2g} = K\frac{v^2Q^2}{2gA^2} = RQ^2$$
$$R = \frac{Kv^2}{2gA^2}$$

where K is a loss coefficient and A is a flow area. v is a specific volume. g refers to the acceleration of gravity. The loss coefficient is obtained from the reactor flow model test results for Hanbit nuclear power plant units 3 and 4, and empirical correlations.

2.4 Results

The original and transformed flow networks were analyzed by VESPER. The core bypass flow rates for the original network are compared to those for Hanbit nuclear power plant units 5 and 6 which had been calculated by NOTTINGHAM. Calculation results of VESPER for the two different networks are compared to each other.

Table I: Core bypass flow rates in the original network

Flow Paths	NOTTINGHAM		VESPER	
	10^6 lbm/hr	%1)	10^6 lbm/hr	%1)
Alignment Keys	0.476	0.391	0.486	0.400
Outlet Nozzle Gaps	1.349	1.111	1.391	1.145
Core Shroud Annulus	0.393	0.323	0.392	0.323
Control Element Guide Tube	0.724	0.596	0.727	0.599
Overall	2.942	2.421	2.996	2.466

1) Ratio to the RCS design flow rate

The analyses were performed under the normal operating condition for OPR1000. The RCS design flow rate is 121.5×10^6 lbm/hr.

As a result, the core bypass flow rates for the original network calculated by the two programs are shown in Table I. The maximum difference of the core bypass flow rates is approximately 4.2×10^4 lbm/hr for the outlet nozzle gaps, which is approximately 0.034% of the RCS design flow rate. The maximum difference of the flow rates for all branches is 0.067%. Therefore the programs are considered to predict substantially the same flow rates. The flow rates are lower than those described in Table 4.4-3 of the OPR1000 final safety analysis report [8]. The core bypass flow rates in the final safety analysis report were conservatively evaluated in a view point of the reactor thermal design. Higher core bypass flow rates make the core thermal margin reduced.

Table II shows the flow rates in the upper guide structure region calculated for the two different networks. Except for the branches in the upper guide structure shown in Table II, the two networks have almost the same flow rates for all branches with the flow rate differences of less than 0.037% of the RCS design flow rate. According to Table II, the flow rates inside the upper guide structure decrease in the transformed network. Especially both of the upward and the downward flows between the upper guide structure and the dome are significantly reduced. It is because the flow passing through the control element guide tubes in the original network is divided into three branches in the transformed network. Although the total flow rate through the control element guide tubes is nearly the same for the two networks, about 2/3 of that through one branch of the original network passes through two other branches directly connected to the nodes 27 and 28 in the transformed network. The two nodes are closer to the downstream of horizontal branch than node 26. Another reason of the reduced flow rates is a doubled resistance by two horizontal branches, but it seems minor because flows through the dome are remarkably reduced despite the same flow rate at the flow path through the alignment keys of the two networks.

Table II: Flow rates in the upper guide structure region1)

Flow Paths	Original Network (a)	Transformed Network(b)	(b)-(a)
UGS2) Support Plate Hole Upward	0.737	0.724	-0.013
UGS Support Plate Hole Downward	2.745	2.732	-0.013
UGS-Dome Upward	1.418	0.794	-0.624
Dome-UGS Downward	1.904	1.280	-0.624
Horizontal inside UGS3)	0.841	0.6064)	-0.235
Control Element Guide Tube	1.522	1.522	0

1) The unit is 10^6 lbm/hr.
2) Upper Guide Structure
3) Nodes 26 to 28 in the original network, and Nodes 26 to 27 and 27 to 28 in the transformed (Refer to Fig. 1.)
4) The higher of two branch flow rates inside the UGS

3. Conclusions

VESPER was developed to improve convergence, accuracy and user convenience. The program employs the gradient method which is excellent to converge a problem with poor initial values and relatively low resistances.

In this study two reactor vessel internal flow networks were analyzed by VESPER. The calculation result by VESPER for the current OPR1000 reactor flow network is substantially the same as that by NOTTINGHAM. The maximum flow rate difference between them is approximately 0.067% of the RCS design flow rate, and only for the core bypass flow rates the maximum difference is approximately 0.034%. The transformed network with the changed upper guide structure and dome flow network from the original network was introduced. The analysis result for the transformed network is almost the same as that for the original network except the flow rates inside the upper guide structure and the dome region. If the flow passing through the control element guide tubes is connected to each of three nodes corresponding to the upper guide structure inside in the transformed network, the flow between the upper guide tube and the dome, and the horizontal flow inside the upper guide structure are evaluated to be significantly reduced compared to that in the original network.

VESPER will supersede NOTTINGHAM. And it will be upgraded so that it is able to perform additional works subsequent to the flow analysis inside the reactor vessel.

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