Journal of the Korean Nuclear Society
Volume 31, Number 3, pp.314~327, June 1999

Development of a Subchannel Analysis Code MATRA Applicable to PWRs and ALWRs

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(Received December 4, 1998)

Abstract

A subchannel analysis code MATRA applicable to PWRs and ALWRs has been developed to be run on an IBM PC or HP WS based on the existing CDC CYBER mainframe version of COBRA-IV-I. This MATRA code is a thermal-hydraulic analysis code based on the subchannel approach for calculating the enthalpy and flow distribution in fuel assemblies and reactor cores for both steady-state and transient conditions. MATRA has been provided with an improved structure, various functions, and models to give more convenient user environment and to enhance the code accuracy. Among them, the pressure drop model has been improved to be applied to non-square-lattice rod arrays, and the models for the lateral transport between adjacent subchannels have been improved to enhance the accuracy in predicting two-phase flow phenomena. The predictions of MATRA were compared with the experimental data on the flow and enthalpy distribution in some sample rod-bundle cases to evaluate the performance of MATRA. All the results revealed that the predictions of MATRA were better than those of COBRA-IV-I.

Key Words : subchannel analysis code, MATRA, PWR, ALWR, COBRA-IV-I

1. Introduction

Subchannel analysis codes are of vital importance in the thermal-hydraulic analysis of nuclear reactor cores. At present, the THINC-IV [1] developed by the Westinghouse Electric Corporation and the TORC [2] developed by the Combustion Engineering, Inc. are being used in the thermal-hydraulic design of the pressurized water reactor (PWR) cores in Korea. Most of the subchannel codes currently used in the design of nuclear reactor cores were developed long ago, and their applicable ranges are limited to the square-lattice rod arrays.

The current worldwide activities related to the reactor-core thermal-hydraulic code development can be classified into three main categories. The first is the fine-mesh approach [3] for the understanding of the local flow phenomena within a subchannel in single-phase flow conditions, especially the characteristics of turbulence around the grid spacers. This is the approach to analyze a problem fundamentally from the microscopic viewpoint; however, its applicability to complex geometry and two-phase flow conditions has not been verified yet. The second is the coarse-mesh approach [4, 5] using a lumped channel consisting of single or multiple assemblies as a unit mesh for the improvement of the analytic capability for two-phase flow fields at transient conditions. This is the approach to accurately analyze the thermal-hydraulic characteristics of a reactor core under the conditions of the loss-of-coolant accident or the reactivity induced accident by being coupled with a system analysis code or a neutronics code. The detailed models of this approach improve the accuracy in predicting two-phase flow conditions; however, its applicability with a subchannel basis is undesirable due to the considerable computing time. The third is the subchannel approach [6] to improve the predictive capabilities with a reasonable computing time by adopting mixture equations and approximate numerical schemes to apply them to the various operating conditions and geometrical configurations of the advanced-type reactors such as advanced light water reactors (ALWRs).

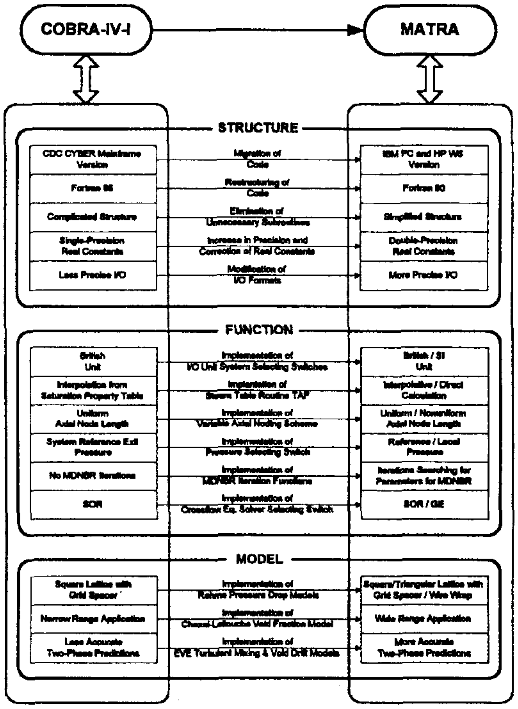

Fig. 1. Comparison of Features Between COBRA-IV-I and MATRA.

We have entered on the development of the subchannel analysis code MATRA (Multichannel Analyzer for steady states and Transients in Rod Arrays) [6, 7] as one of the activities based on the aforementioned third approach. MATRA is the thermal-hydraulic analysis code being developed at the Korea Atomic Energy Research Institute (KAERI) based on the subchannel approach for calculating the enthalpy and flow distribution in rod bundle nuclear fuel elements and reactor cores for both steady-state and transient conditions. Because there must be two-phase states under the critical heat flux (CHF) conditions, the improved analytic capability of the subchannel code for two-phase flow fields is required. In addition, to apply the subchannel analysis to the design of ALWRs considering various core conditions, it is necessary to develop the subchannel code technology producing the reliable analysis results in various operating conditions and geometrical configurations.

In the MATRA code, we focused on the implementation of the code features to give more convenient user environment, the pressure drop models for non-square-lattice rod arrays to be applied to the analysis of ALWR cores, and the improved models for the lateral transport between adjacent subchannels to improve the predictive capability for two-phase flow fields. The detailed key features of MATRA are described in the following chapter.

2. Features of MATRA

This chapter describes the additional features of

MATRA with classifying them into three viewpoints, i.e., the improved code structure, newly implemented functions, and newly implemented models. All of these features of MATRA are shown in Fig. 1 compared with those of COBRA-IV-I [8], the reference code of MATRA.

2.1. Improved Structure

We have provided MATRA with the improved code structure to give the more convenient user interface and working environment, and to enhance the code accuracy by the various methods described in the following subsections.

2.1.1. Migration of Code

The existing COBRA-IV-I code is the CDC (Control Data Corporation) CYBER mainframe version, which has the limitation on the computer core storage and gives some inconvenience to the user interface. To solve these problems, we converted COBRA-IV-I to the HP WS (Hewlett Packard Workstation) (9000/700-series) version, and verified the converted code. [9] Moreover, we have converted the code to the IBM PC (International Business Machines Personal Computer) (and compatible computers) and HP WS version to expand the user working environment.

2.1.2. Restructuring of Code

COBRA-IV-I was programmed with Fortran 66, which requires statement labels and 'GOTO' statements in the construction of certain standard control structures. They do interrupt one's reading and modifying of a program. Therefore, we have restructured the code and converted the language to Fortran 90, which provides a code with the readability and maintainability.

2.1.3. Elimination of Unnecessary Subroutines

In COBRA-IV-I, a number of subroutines are used for the editing of incorrect input data prepared by the user. Although these subroutines are unnecessary in main calculations, they are large in size and interrupt one's reading of the code. Therefore, we have eliminated these subroutines and have simplified the code structure.

2.1.4. Increase in Precision and Correction of Real Constants

All the real variables and constants used in MATRA are declared implicitly as type double-precision real. Some important real constants used in calculations, however, had the single precision and/or incorrect values. Therefore, we have corrected the values and have increased the number of significant decimal digits of the real constants to obtain the improved code accuracy.

2.1.5. Modification of Input/Output Formats

The insufficient significant figures of the input data of COBRA-IV-I due to the existing input format produce the round-off errors that are not negligible. Therefore, we have inevitably changed the input format so that all the input of both types, real and integer, may take 10 digits in MATRA. In addition, we have changed the output format so that the more significant figures of the important parameters can be printed out to obtain the improved accuracy of a postprocess.

2.2. Implemented Functions

We have provided MATRA with various functions to give the more convenient user working environment and to enhance the code accuracy. These functions are described in the following subsections.

2.2.1. Input/Output Unit System Selecting Switches

In COBRA-IV-I, only the British unit system can be used for the units of both input and output data. Thus, in the case of the calculation using the input data in the units of the International System of Units (SI), the input data should be prepared by converting from the SI to the British units, which would cause the round-off errors affecting the calculation results of the code. Therefore, we have implemented the switch for selecting the input/output unit systems between the British and SI ones in MATRA, which allows the selective use of the British and SI unit systems for both input and output.

2.2.2. Steam Table Routine TAF

In COBRA-IV-I, the subcooled properties of a fluid are calculated by interpolation using the saturation property table supplied by the user, which leads to the considerable errors in the calculation results of the code. Therefore, we have implanted the steam table routine TAF [10] to MATRA to calculate subcooled properties directly by referencing the function TAF, which improves the accuracy in calculating subcooled properties.

2.2.3. Variable Axial Noding Scheme

In COBRA-IV-I, only the uniform-length axial nodes can be used in calculations. Thus, in the case of the problem that requires the detailed analysis for the local interested region such as the flow blockage, the other uninterested regions also should be inevitably analyzed in detail, which would increase the computer running time and required memory. Therefore, we have implemented the variable axial noding scheme in MATRA to use dense axial nodes selectively for interested regions, which allows the optimization of the number of axial nodes in calculations.

2.2.4. Pressure Selecting Switch

In COBRA-IV-I, all the fluid properties are calculated at the system exit pressure as the reference one. This can be regarded as reasonable in the high-pressure conditions of the commercial reactors such as PWRs and boiling water reactors (BWRs) because the effect of the axial pressure drop over the rod bundle on fluid properties is negligibly small. In the low-pressure conditions of the research reactors such as the Hi-flux Advanced Neutron Application Reactor (HANARO), i.e., the Korea Multi-purpose Research Reactor (KMRR), however, the pressure-drop effect on fluid properties is considerable, especially on the fluid densities in two-phase flow conditions. Therefore, we have implemented the switch for selecting the pressure used in the calculation of fluid properties between the reference and local pressures in MATRA to account for the effect of the local pressure on the fluid properties in low-pressure, two-phase flow conditions.

2.2.5. MDNBR Iteration Functions

The most limiting constraint on the thermal power output of a current PWR core is a minimum departure from nucleate boiling ratio (MDNBR). Because the MDNBR is a limit of the core power capability and the operational flexibility of most PWRs, it is necessary to calculate the operating boundaries corresponding to a predetermined limit DNBR. Therefore, we have implemented the MDNBR iteration functions, which iteratively search for the values of the parameters such as power, rod radial peaking factor, and flow to produce a desired MDNBR.

2.2.6. Crossflow Equation Solver Selecting Switch

The overall solution scheme of MATRA or COBRA-IV-I, as shown in Fig. 2, consists of an external iterative sweep of the computational mesh from inlet to exit in which the local values of enthalpy (h), density (ρ), crossflow (w), axial flow (m), and pressure (p) are updated at each axial level in turn. This involves two additional internal iterative solutions for the enthalpies in all subchannels and the crossflows in all gaps at each axial level. The external solution is considered to be converged when the maximum changes in crossflow and axial flow are simultaneously less than the specified input values between successive external iterations. If the convergence criteria are not satisfied after a specified number of external iterations, the calculation is terminated. Convergence criteria and maximum iterations are similarly specified for the two internal iterative solutions but the solution is allowed to continue whether or not these are satisfied. In COBRA-IV-I, the successive over-relaxation (SOR), i.e., the Gauss-Seidel iteration method with over-relaxation, is used to compute crossflows between adjacent subchannels. However, because of the slow rate of convergence of this method, many external iterations are usually needed to achieve the desired accuracy in calculation of core thermal-hydraulic parameters. As an alternative method for solution of crossflow equations, therefore, we have chosen the direct equation solver, i.e., the Gaussian elimination (GE). The higher accuracy achieved by using the GE method increases the rate of convergence of the external iteration scheme used in solving the implicit boundary value problem. Thus, we have implemented the switch for selecting the diversion-crossflow equation solver between SOR and GE in MATRA.

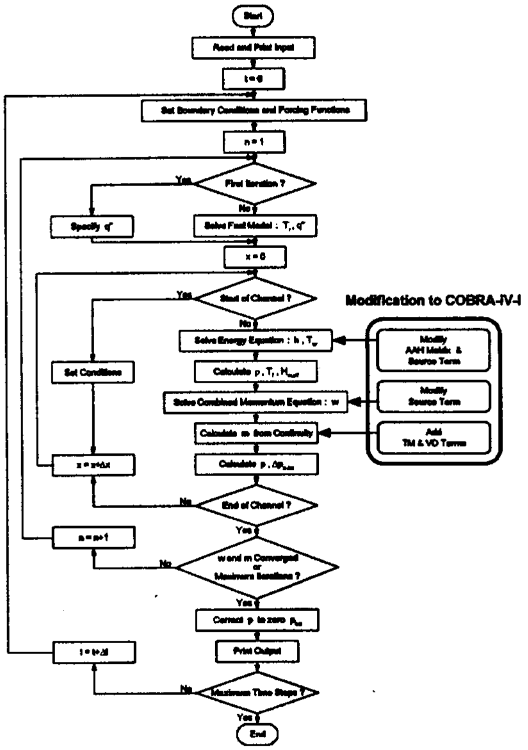

Fig. 2. Flowchart for Implicit Scheme of MATRA.

2.3. Implemented Models

We have provided MATRA with some improved models to enhance the code accuracy in analyzing non-square-lattice rod arrays and two-phase flow fields. These models are described in the following subsections.

2.3.1. Non-Square-Lattice Pressure Drop Models

At present, MATRA uses nearly the same

governing equations as those of COBRA-IV-I [8, 11], which were derived so that various channel configurations or rod arrays could be analyzed. Thus, there are no great problems in analyzing various types of reactor core with COBRA-IV-I. For more accurate analyses, however, it was necessary to implement appropriate pressure drop models, and therefore, we have implemented the Rehme's pressure drop models for the triangular rod arrays with wire wraps [12] and without wire wraps [13] in MATRA.

In the case of wire wrapped rod bundles with triangular arrangement of rods, Rehme developed the pressure drop correlation of general validity by the systematic measurements with 80 different arrangements of wire wrapped rod bundles. The important parameters varied in his study are the pitch-to-diameter ratio of the rod, ranging between 1.125 and 1.417, by using different wire wrap diameters with the same rod diameter, the lead-to-diameter ratio of the wire wrap, ranging between 6 and 45, and the number of rods in a rod bundle, ranging between 7 and 61. The Reynolds numbers considered in his study ranging between 10^3 and 3×10^5.

In the case of bare rod bundles with a triangular arrangement of rods, Rehme developed the pressure drop correlation based on the concept of an "equivalent annular zone" by the systematic measurements with 25 test sections of bare rod bundles in hexagonal channels. The important parameters varied in his study are the pitch-to-diameter ratio of the rod, ranging between 1.025 and 2.324, by using the same rod diameter, and the number of rods in a rod bundle, ranging between 7 and 61. The Reynolds numbers considered in his study ranging between 6×10^2 and 2×10^5.

2.3.2. Wide-Range Applicable Void Fraction Model

In COBRA-IV-I, a few void fraction models are used to predict the saturated void fraction in two-phase flow fields. These models, however, are very simple and out of date, so they can be applied to only narrow-range conditions. Therefore, we have implemented the improved wide-range applicable Chexal-Lellouche void fraction model [14] in MATRA.

The Chexal-Lellouche correlation was developed to cover the full range of pressures, flows, void fractions, and fluid types (steam-water, air-water, hydrocarbons, and oxygen). The correlation was qualified against several sets of steady-state two-phase/two-component flow test data that cover a wide range of thermodynamic conditions and geometries typical of PWR and BWR fuel assemblies as well as for pipes up to 450 mm in diameter. The correlation is based on a drift flux model and determines the drift flux parameters, C_0, concentration parameter, and V_{gj}, drift velocity, for both cocurrent and countercurrent two-phase flows for the full range of pressures, flows, and void fractions. The correlation is continuous and does not depend on flow regime maps.

2.3.3. Improved Lateral Transport Models

In general, subchannel codes use the one-dimensional approach based on the assumption of the axially dominant flow. Consequently, subchannel codes consider the lateral transport phenomena that occur between adjacent subchannels with simple models, and thus, the effects of these lateral transport models on the accuracies of subchannel codes are considerable.

The lateral transport phenomena are quite complicated and difficult to decompose into more elementary interchange terms. Nevertheless, they normally are decomposed arbitrarily into the following several components [15, 16]:

1. *Diversion crossflow* : the directed flow due to

the lateral pressure difference between adjacent subchannels;

2. *Turbulent mixing* : the exchange of fluid due to the random fluctuating motion, which does not favor a particular direction;
3. *Void drift* : the migration of void due to the strong tendency of the two-phase system to approach an equilibrium phase distribution;
4. *Molecular diffusion* : the exchange of molecules due to the random kinetic dispersion;
5. *Deflected crossflow* : the directed flow due to some artificial means such as wire wraps or deflecting vanes;
6. *Forced mixing* : the exchange of fluid due to some artificial means such as grid spacers, which does not favor a particular direction.

Among them, the diversion crossflow and molecular diffusion phenomena are considered in the governing equations; the deflected crossflow and forced mixing phenomena are experimentally determined from the geometrical characteristics of the structures. Consequently, the modelings of the turbulent mixing and void drift phenomena are very important.

In COBRA-IV-I, the equal-mass-exchange (EME) model is employed as a turbulent mixing model, but the void drift phenomenon is not considered. In single-phase flow conditions, the predictions by the EME turbulent mixing model are nearly the same as those of the equal-volume-exchange (EVE) model. In two-phase flow conditions, however, the predictions by the EVE model are known as better. [16] Because the void drift phenomenon occurs due to the void distributions in subchannels, it is hardly considered in the analysis of the PWR core under the steady-state operating condition in which two-phase flow phenomena do not prevail. In the postulated accident or critical heat flux (CHF) conditions, however, there would be a substantial amount of void in subchannels, and thus, the void drift model is expected to greatly affect the accuracies of subchannel codes. Therefore, we have implemented the Lahey et al. [16]'s EVE turbulent mixing model using the Beus [15]'s two-phase turbulent mixing multiplier, and the flow-pattern-dependent void drift model [17] with modification to the Lahey et al. [16]'s model using the Levy [18]'s equilibrium density distribution model in MATRA.

The governing equations of MATRA for mass, energy, and axial momentum are as follows:

for mass,

$$A_i \frac{\partial \rho_i}{\partial t} + \frac{\partial m_i}{\partial x} + \sum_j w_{ij} + \underline{\sum_j w'_{i\leftrightarrow j}} = 0; \tag{1}$$

for energy,

$$A_i \frac{\partial (\rho_i h_i)}{\partial t} + \frac{\partial (m_i \hat{h}_i)}{\partial x} + \sum_j w_{ij} \hat{h}^* + \sum_j (q''s)'_{i\leftrightarrow j} = Q_i; \tag{2}$$

for axial momentum,

$$\frac{\partial m_i}{\partial t} + \frac{\partial}{\partial x}\left(\frac{m_i^2 v'_i}{A_i}\right) + \sum_j w_{ij} u^* + \underline{\sum_j (\tau s)'_{i\leftrightarrow j}} = -A_i \frac{\partial p_i}{\partial x} - F_{x,j}; \tag{3}$$

where the underlined terms are the modifications to COBRA-IV-I and their implementation in the calculation procedure of MATRA is shown in Fig. 2. The newly implemented lateral transport terms, i.e., $w'_{i\leftrightarrow j}$, $(q''s)'_{i\leftrightarrow j}$, and $(\tau s)'_{i\leftrightarrow j}$, in two-phase flow conditions are represented as follows:

$$w'_{i\leftrightarrow j} = w'_{ij}\, \theta \left[(\alpha_j - \alpha_i) - C_{VD} \frac{\alpha_{avg}}{G_{avg}} (G_j - G_i) \right]; \tag{4}$$

$$(q''s)'_{i\leftrightarrow j} = w'_{ij}\, \theta \left[(\alpha_j - \alpha_i) - C_{VD} \frac{\alpha_{avg}}{G_{avg}} (G_j - G_i) \right] h_{eff}; \tag{5}$$

$$(\tau s)'_{i\leftrightarrow j} = f_T\, w'_{ij}\, \theta \left[(\alpha_j - \alpha_i) - C_{VD} \frac{\alpha_{avg}}{G_{avg}} (G_j - G_i) \right] u_{eff}; \tag{6}$$

where C_{VD} is the flow-pattern-dependent void drift

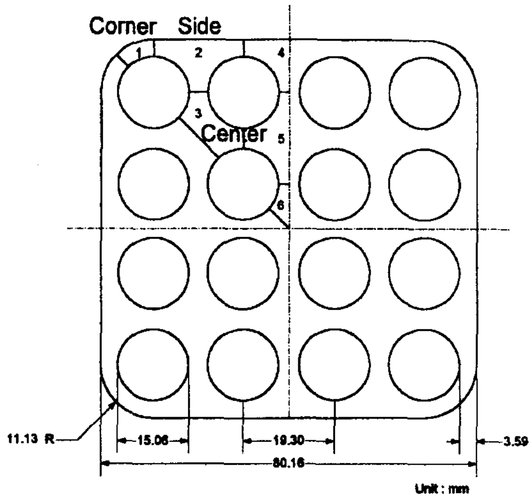

Fig. 3. Cross-Sectional View of CNEN-Studsvik 16-Rod Bundle.

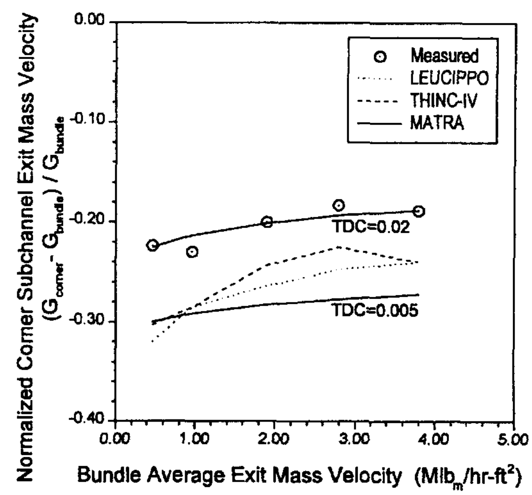

Fig. 4. Corner Subchannel Exit Mass Velocities for CNEN-Studsvik Isothermal Flow Test.

correction factor determined empirically for the present. Through the analysis of two-phase experimental data, we have obtained the values of C_{VD} according to the two-phase flow pattern as follows [17]:

at BWR conditions with the pressure of about 70 bar,

$$C_{VD} = \begin{cases} 1.5 & \text{for } \chi < \chi_C \text{ (slug flow)} \\ 5.0 & \text{for } \chi \geq \chi_C \text{ (annular flow)} \end{cases}; \tag{7}$$

at PWR conditions with the pressure of about 160 bar,

$$C_{VD} = 0. \text{ (dispersed bubbly flow)}, \tag{8}$$

where the boundary value of quality is determined from the Steen-Wallis criterion [16] as

$$\chi_C = \frac{0.4\sqrt{gD_{hy}\rho_f \Delta\rho}/G + 0.6}{\sqrt{\rho_f/\rho_g} + 0.6}. \tag{9}$$

3. Verification of MATRA

This chapter describes the analysis results of the sample problems selected to evaluate the performances of the representative items among the additional features of MATRA.

3.1. CNEN-Studsvik Isothermal Flow Test

To evaluate the fundamental predictive performance of MATRA, we analyzed the experimental data of velocity measurements from the isothermal flow test performed under the atmospheric pressure and room temperature at the Studsvik Laboratory with MATRA. Kjellen et al. [19] measured the axial velocity and temperature distributions in a 4×4 rod bundle to obtain the information about the heat transfer due to turbulent mixing between adjacent subchannels in single-phase flow conditions.

The geometry of the cross-section of the rod bundle is shown in Fig. 3 with a subchannel numbering scheme used in MATRA. For the five bundle-average mass velocities, the mass velocities at the corner subchannel exit predicted by MATRA are shown in Fig. 4 with those predicted

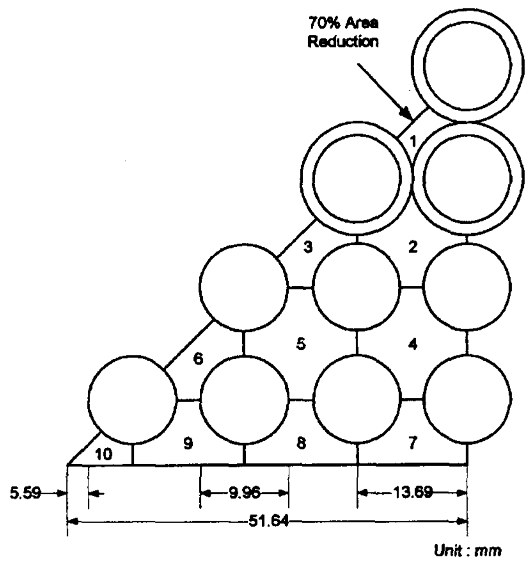

Fig. 5. Cross-Sectional View of PNL 49-Rod Bundle (1/8 Symmetry).

by the LEUCIPPO [19] of the CNEN (Comitato Nazionale per l'Energia Nucleare) in Italy and the THINC-IV [1] of the Westinghouse Electric Corporation, and the measured data. As shown in Fig. 4, MATRA has the predictive performance similar to those of the other codes.

3.2. PNL Isothermal Flow Blockage Test

To evaluate the performance of the variable axial noding scheme implemented in MATRA, we analyzed the experimental data from the isothermal flow blockage test performed at the Pacific Northwest Laboratories (PNL) with MATRA. Creer et al. [20] measured the axial velocity, turbulent intensity, and turbulent scale values in an unheated 7×7 rod bundle containing partial flow blockages. The experiment was undertaken to improve the understanding of flow distributions in partially blocked rod bundles during a loss-of-coolant accident, and to aid in verifying the capability of COBRA-IV-I to perform flow blockage analyses.

The geometry of the 1/8 cross-section of the rod bundle containing partial flow blockages is shown in Fig. 5 with a subchannel numbering scheme used in MATRA. To show the accuracy and efficiency of the calculation using the variable axial noding scheme, we analyzed the experimental data with COBRA-IV-I using the uniform axial noding scheme and with MATRA using a nonuniform axial noding scheme with the same number of axial nodes as shown in Fig. 6. The axial distributions of axial velocities obtained from the analyses by COBRA-IV-I and MATRA are shown in Fig. 7 with the measured data. As shown in Fig. 7, compared with the COBRA-IV-I using uniform-length axial nodes, the MATRA using nonuniform-length axial nodes predicted the measured data better, especially in the blocked region. From the analysis results, the variable axial noding scheme implemented in MATRA is expected to optimize the number of axial nodes required in calculations.

3.3. GE and ISPRA Two-Phase Flow Tests

To evaluate the performances of the improved lateral transport models, i.e., the EVE turbulent mixing and the flow-pattern-dependent void drift models, implemented in MATRA, we analyzed the experimental data from the two-phase flow tests performed at the General Electric Company (GE) and the ISPRA in Italy with MATRA. Lahey et al. [21] measured the enthalpy and flow distributions at the exits of the representative corner, side, and center subchannels in an electrically heated 3×3 rod bundle under the pressure of 69 bar, typical of BWR operating conditions. Similarly, Herkenrath et al. [22] measured the enthalpy and flow distributions at the exits of the representative corner, side, inner, and center subchannels in two different types of electrically heated 4×4 rod

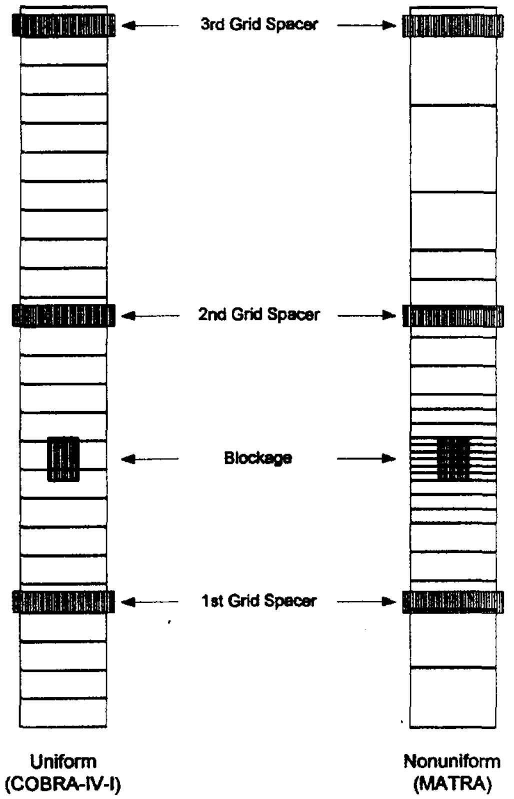

Fig. 6. Axial Noding Schemes of COBRA-IV-I and MATRA for PNL Isothermal Flow Blockage Test (No. of Axial Nodes = 25).

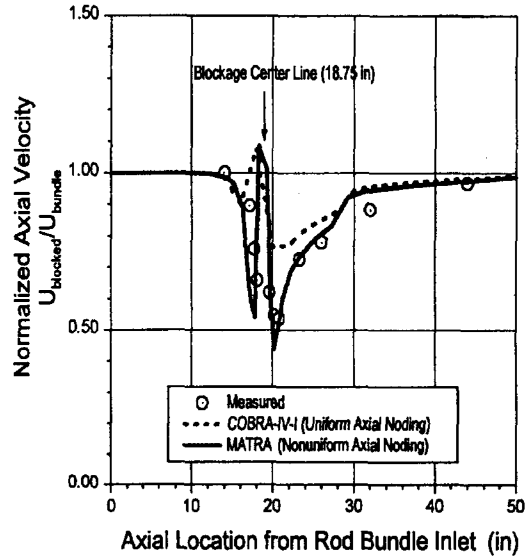

Fig. 7. Axial Velocity Distributions in Blocked Subchannel for PNL Isothermal Flow Blockage Test.

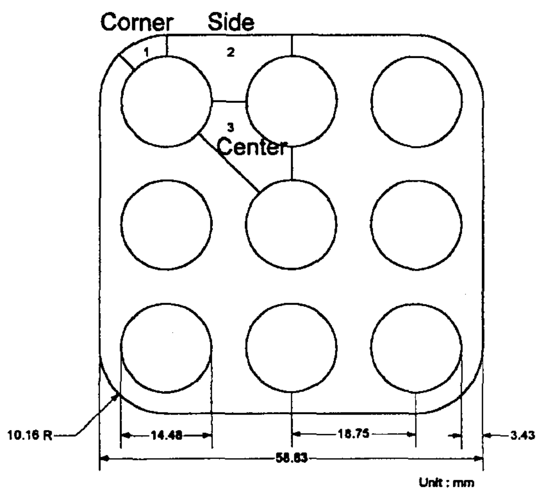

Fig. 8. Cross-Sectional View of GE 9-Rod Bundle.

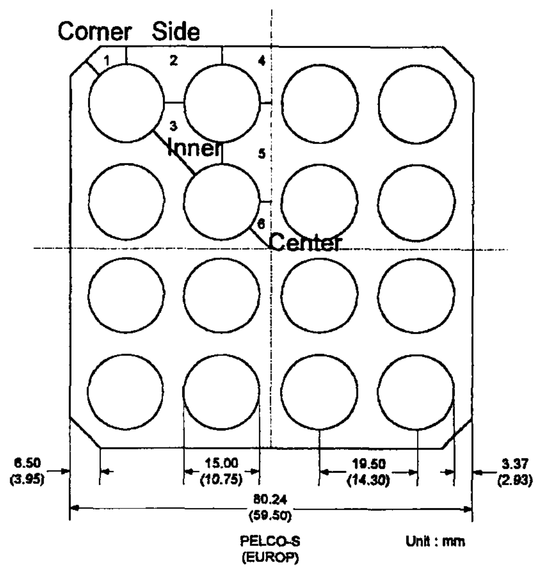

Fig. 9. Cross-Sectional View of ISPRA 16-Rod Bundles PELCO-S and EUROP.

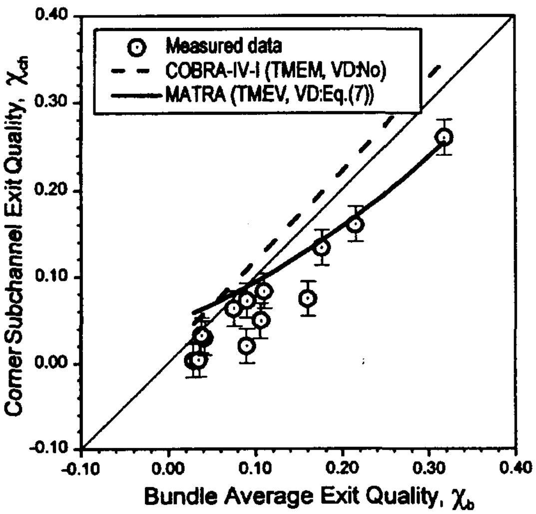

Fig. 10. Corner Subchannel Exit Qualities for GE 9-Rod Bundle Test).

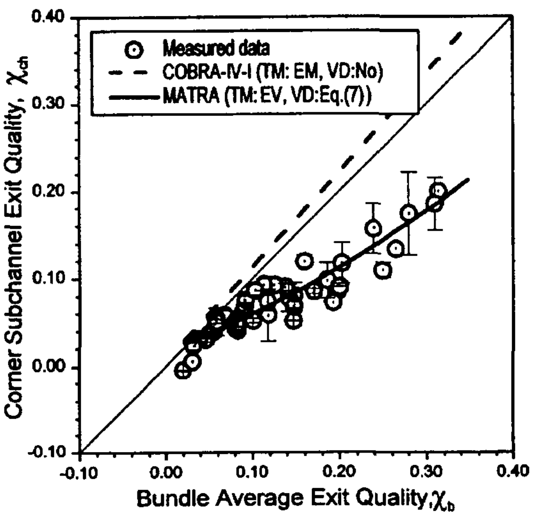

Fig. 11. Corner Subchannel Exit Qualities for ISPRA 16-Rod Bundle Test (PELCO-S).

bundle with typical geometries for BWRs (PELCO-S) and PWRs (EUROP) under the pressure of 70 bar, typical of BWR conditions

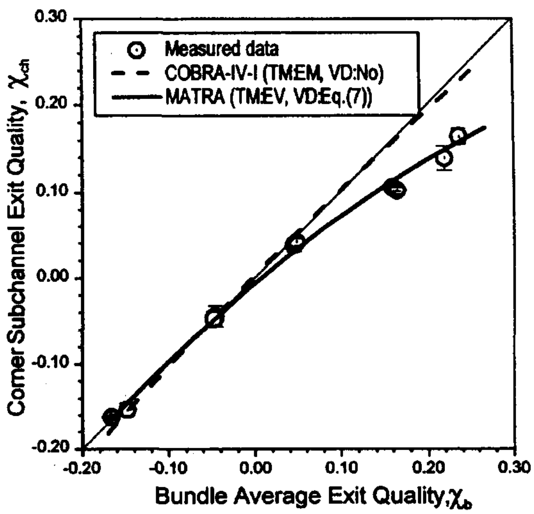

Fig. 12. Corner Subchannel Exit Qualities for ISPRA 16-Rod Bundle Test (EUROP-70).

(PELCO-S, EUROP-70) and the pressure of 160 bar, typical of PWR conditions (EUROP-160).

The geometries of the cross-sections of the GE 9-rod bundle and ISPRA 16-rod bundles are shown in Figs. 8 and 9, respectively, with subchannel numbering schemes used in MATRA. For the GE and ISPRA (PELCO-S, EUROP-70) two-phase flow tests, the exit qualities in the corner subchannel predicted by MATRA using the EVE turbulent mixing and the flow-pattern-dependent void drift models with the void drift correction factors of 1.5 for slug flow regime and 5.0 for annular flow regime are shown in Figs. 10 through 12, with those predicted by COBRA-IV-I using the existing EME turbulent mixing model only, and the measured data. As shown in Figs. 10 through 12, MATRA using the EVE turbulent mixing and the flow-regime-dependent void drift models predicted the lower-than-average qualities in the corner subchannels observed in the experiments better than COBRA-IV-I.

4. Conclusions and Further Works

A subchannel analysis code MATRA running on an IBM PC or HP WS has been developed, and its performance has been evaluated by comparing its predictions with experimental data. MATRA has been provided with various features to be applied to the analysis of ALWR cores as well as the existing PWR cores. In addition, the models for the lateral transport between adjacent subchannels have been improved, and as the result, it revealed that the performance of MATRA in predicting two-phase flow phenomena was better than that of the existing COBRA-IV-I code.

MATRA will be provided with the improved numerical stability in the analysis of two-phase and low flow fields, the improved performance in analyzing transient states, and the capability of considering the thermal nonequilibrium state as future works.

Acknowledgement

The authors express their appreciation to the Ministry of Science and Technology (MOST) of Korea for the support.

Nomenclature

A	axial flow area
C_{VD}	flow-pattern-dependent void drift correction factor: defined in Eqs. (7) and (8)
D_{hy}	hydraulic diameter
F_x	force exerted in the axial direction per unit axial length
f_T	turbulent momentum factor
G	axial mass velocity
g	gravitational acceleration
h	static enthalpy
$\hat{h}$	flow enthalpy
$\hat{h}^*$	flow enthalpy transported by diversion crossflow
h_{eff}	effective mixing enthalpy: $h_{eff} \equiv (\rho_f h_f - \rho_g h_g)/\Delta\rho$
m	axial mass flow rate
p	pressure
Q	heat input per unit axial length
q''	heat flux
$(q''s)'_{i\leftrightarrow j}$	net rate of lateral energy transport per unit axial length due to turbulent mixing and void drift: defined in Eq. (5)
s	gap spacing between adjacent subchannels
t	time
u	axial velocity
u^*	axial velocity transported by diversion crossflow
u_{eff}	effective mixing axial velocity: $u_{eff} \equiv (\rho_f u_f - \rho_g u_g)/\Delta\rho$
w_{ij}	diversion crossflow from subchannel i to subchannel j
w'_{ij}	turbulent mixing flow rate per unit axial length
$w'_{i\leftrightarrow j}$	net rate of lateral mass transport per unit axial length due to turbulent mixing and void drift: defined in Eq. (4)
x	axial coordinate

Greek Letters

α	void fraction
$\Delta\rho$	difference in density between saturated liquid and vapor: $\Delta\rho \equiv \rho_f - \rho_g$
θ	two-phase turbulent mixing multiplier
ρ	mixture density
τ	shear stress
$(\tau s)'_{i\leftrightarrow j}$	net rate of lateral axial momentum transport per unit axial length due to turbulent mixing and void drift: defined in Eq. (6)
χ	quality
χ_C	quality at the slug-to-annular transition: defined in Eq. (9)

v' momentum specific volume

Subscripts

avg average weighted by adjacent subchannel axial flow areas

f, g saturated liquid and vapor, respectively

i, j index for donor and receiver subchannel, respectively

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