Validation of MATRA-S for Core Pressure Drop Analysis in SMART Application

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1. Introduction

Evaluation of core pressure drop or fuel assembly (FA) pressure drop is of importance in thermal-hydraulic reactor design activities in relevant to design of a primary coolant pump. In addition, it can be used as an input parameter for the estimates of uplift drag forces exerting on FAs. From a wider perspective, prediction capability for local pressure drop across FA components such as mixing vanes and nozzles are related to predictions of local flows and void distributions within core, which are connected to the evaluation of thermal margin in a reactor core.

Generally, a classical fluid mechanics relationship of pressure drop with the form loss and friction factor, with the aid of results from out-pile hydraulic testing have been used in design of existing commercialized pressurized light water reactors, which is extracted based on the assumptions of steady-state, incompressible, single-phase, isothermal flows. On the other hand, a subchannel analysis code can be used for core pressure drop analysis where appropriate constitutive correlations for its application are adopted in the code, which is assured by validations with reliable data obtained from out-pile testing. For this purpose, a subchannel analysis code, MATRA-S[1], has been updated and a validation study with the implemented models has been conducted. Prediction accuracies are also quantified which provides a basis for design uncertainties of core pressure drop when present methodologies are used in SMART application.

2. Validation Experiments

As an out-pile experiments, full-scale 17×17 fuel assembly and fuel simulator arranged in 5×5 square arrays have been tested at KAERI[2] and Stern laboratory[3], respectively, in order to determine thermal-hydraulic characteristics of SMART fuel assemblies. Pressure drop data obtained from these experiments are employed in model development and code validation. Geometric information of test bundle and experimental conditions are briefly described below.

2.1 PLUTO Full-scale Fuel Assembly

Pressure drops across a single 17×17 SMART FA under single-phase isothermal conditions were measured at PLUTO (Performance Test for Fuel Assembly Hydraulics & Vibration) test facility, to determine hydraulic loss coefficients of spacer grids and nozzles of SMART FA. The test was performed as varying flow rates at predetermined cold and hot conditions (65 and 121°C) to cover wide range of Reynolds number (*Re*= 60,000~210,000).

Equivalent diameter of test rig (=10.14 mm) is similar to SMART FA but slightly reduced by increase of total perimeter owing to surrounding housing walls. Axially, test bundle resides in the middle of the flow housing with having upper and lower parts and total length of measurements is >3000.0 mm. Here, a schematic diagram for 1-D nodalization used in MATRA analysis is illustrated to show locations of FA components within flow housing.

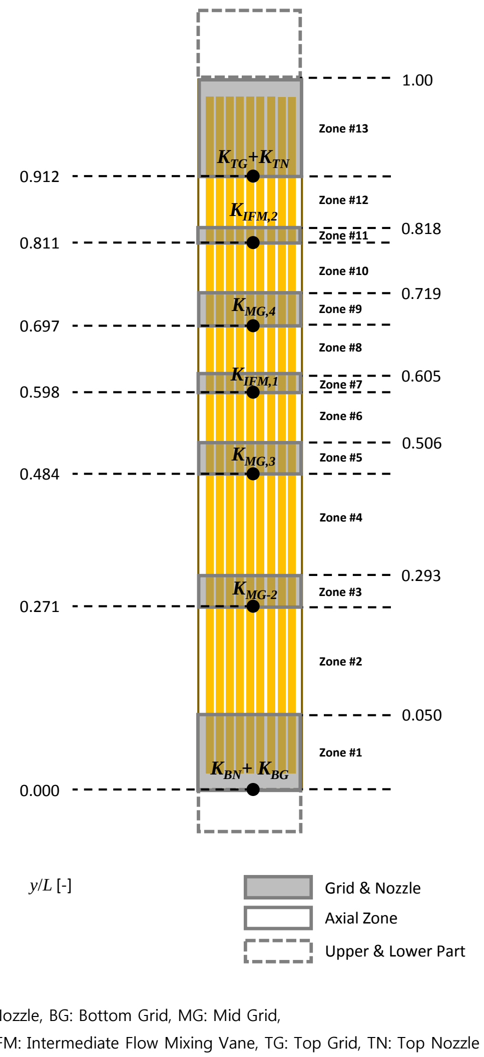

Fig. 1. Schematics of PLUTO full-scale test bundle

2.2 SMART 5×5 Fuel Rod Simulator

Stern laboratory measured single- and two-phase flow pressure drop with SMART 5×5 fuel bundle under uniform axial heat flux conditions. Two-types of fuel bundles called C-1 and C-3 were used. There is no difference between two types of bundles but an unheated rod with 28.8% larger diameter is located at the center of bundle instead of a nominal heated rod in C-3 bundle which result in smaller hydraulic equivalent diameter and smaller heated equivalent diameter of subchannels compared to C-1 bundle. Unlike the test bundle used in PLUTO experiment, the active region of SMART FA is only reflected on SMART 5×5 fuel rod simulator which contains two IFM girds and three mid grids.

All tests were conducted at conditions over 7.0 MPa, 150°C while varying mass flow rate to cover wide range of Reynolds number (*Re*= 17,300~214,000).

3. MATRA-S Models

3.1 Subchannel Momentum Balance

The combined momentum balance which is directly related to calculation of pressure drop is derived based on control volumes of subchannels in development of MATRA-S code[1]:

$$\underbrace{\bar{A}_{I,j}\frac{P_{I,j}-P_{I,j-1}}{\Delta x_j}}_{\text{Axial pressure force term}} = -\underbrace{\frac{\dot{m}_{I,j}-\dot{m}_{I,j}^{n-1}}{\Delta t}}_{\text{Transient term}} - \underbrace{\frac{1}{\Delta x_j}\left(\frac{\dot{m}_{I,j}^2}{\rho'_{I,j}A_{I,j}}-\frac{\dot{m}_{I,j-1}^2}{\rho'_{I,j-1}A_{I,j-1}}\right)}_{\text{Axial convection}}$$
$$-\underbrace{\sum_J W_{IJ,j}\left(U'_{IJ,j}\right)}_{\text{Lateral convection}} - \underbrace{\sum_J f_T w'_{IJ,j}\left(U'_{I,j}-U'_{J,j}\right)}_{\text{Turbulent momentum mixing}}$$
$$-\underbrace{\bar{A}_{I,j}\rho_{I,j}g\cos\theta}_{\text{gravity force}} - \underbrace{\left(\frac{\dot{m}_{I,j}^2}{A_{I,j}}\right)F_{I,j}}_{\text{External force term}} \quad (3.1)$$

The terms in Eq. (3.1) can be classified into transition, axial convection, lateral convection, turbulent momentum mixing, and gravitational and external forces, which are related to each components of pressure drop. For nominal condition, majority of pressure drop is generally caused by external force and gravity force term within fuel bundle. External force term can be divided into frictional loss of rods and pressure loss due to grids and nozzles as seen in the equation below:

$$F_{I,j}=\left[\frac{f}{2d_{hy}\rho'}+\frac{K}{2\rho'\Delta x}\right] \quad (3.2)$$

The irreversible pressure drop defined as the total pressure drop minus gravitational pressure drop is generally required to evaluate the total pressure loss in a closed loop system such as primary loop of a reactor core. In order to extract the irreversible pressure drop from code results, MATRA-S is modified to enable printing out each components of pressure drop based on the momentum balance above.

3.2 Friction Factor and Loss coefficients

In the PLUTO experiment, it was found that loss coefficients of FA components of full-scale SMART FA show a similar functional form of Reynolds number to the Blasius' or McAdams's friction factor:

$$K = a\,\mathrm{Re}^b + c \quad (3.3)$$

In case of a friction factor for bare rods, Eq. (3.3) is still valid when $f(L/D)$ is substituted for the loss coefficient, K. Coefficients of Eq. (3.3) which characterize hydraulic resistances of fuel bundles are determined based on out-pile test results. Previously, constant loss coefficients can be only inserted in MATRA code to assign each FA components in specified subchannels. In order to reflect these kinds of hydraulic characteristics for modeling SMART FA, MATRA-S is modified to enable to use Reynolds-dependent K models.

3.3 Two-phase Multiplier

In order to consider two-phase flow effects on pressure drop in MATRA-S calculation, Armand two-phase multiplier model[4] is selected in which the two-phase multiplier is correlated with void fraction and quality of two-phase flow as follows:

$$\begin{aligned}\phi_{2-\phi}^2 &= \frac{(1-x)^2}{(1-\alpha)^{1.42}} && \text{, for } 0<\alpha<0.6\\ &= 0.478\times\frac{(1-x)^2}{(1-\alpha)^{2.2}} && \text{, for } 0.6<\alpha<0.9\\ &= 1.73\times\frac{(1-x)^2}{(1-\alpha)^{1.64}} && \text{, for } 0.9<\alpha<1.0\end{aligned} \quad (3.4)$$

Void fraction distributions for subcooled flow boiling and saturated flow boiling regimes are calculated in MATRA-S by Saha-Zuber model[5] and homogeneous model, respectively.

4. Results and Discussion

4.1 Single-phase Flow

The prediction results of MATRA-S for axial averaged bundle pressure in PLUTO full-scale SMART FA under cold and hot conditions are representatively shown in Fig. 2. It shows that the model for loss coefficients of full-scale SMART FA are appropriately optimized for wide range of conditions and well implemented in MATRA-S code. As expected, the irreversible pressure drops across full-scale SMART FA also can be estimated (within ±7.0%) with high confidential level (see Fig. 3).

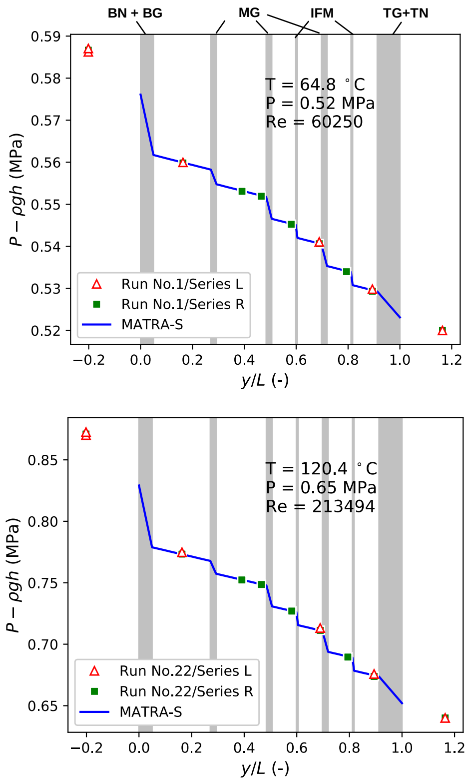

Fig. 2. Comparison between full-scale SMART FA local pressure data and MATRA-S results (single-phase)

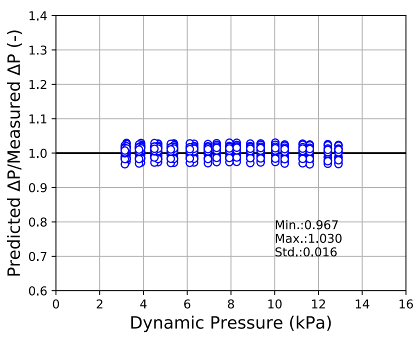

Fig. 3. MATRA-S predictions (P) over measured pressure drop data (M) for full-scale SMART FA (single-phase)

Fig. 4 shows the prediction results of MATRA-S for pressure distributions along axial direction in SMART 5×5 rod bundles under single-phase flow conditions. As seen in this figure, a good agreement between data and code simulations for bundle pressure at any axial location of FA are found in both C-1 and C-3 5×5 SMART FAs. Even though, however, slight over-estimates are found in case of C-3 test bundle with the maximum absolute error of 6.6 % (Fig. 5). It seems to be due to loss coefficients and friction factor which were optimized based on test results with full-scale bundle of which diameter is deviated from that of C-3 test section.

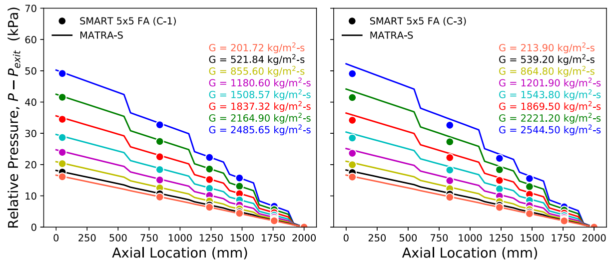

Fig. 4. Comparison between SMART 5x5 bundle pressure data and MATRA-S results (single-phase)

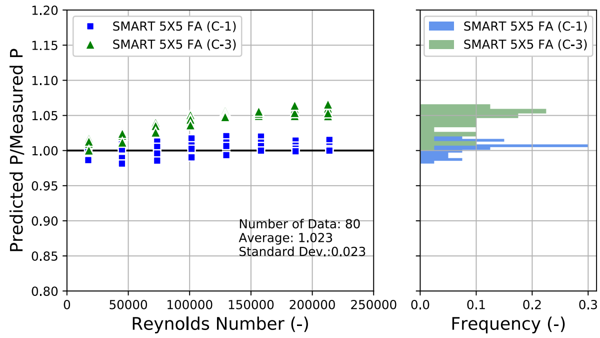

Fig. 5. MATRA-S predictions (P) over measured local pressure data (M) for SMART 5×5 fuel bundle (single-phase)

4.2 Two-phase Flow

MATRA-S models are also validated for two-phase flow pressure drop data which were obtained from SMART 5×5 FA simulators. It has been verified that MATRA-S with the models of two phase multiplier described in Section 3.3 overestimates FA pressure drop for low pressure conditions (<11.5 MPa) but shows fairly good predictions for high pressure conditions (>11.5 MPa). The minimum and maximum errors for high pressure conditions which contain the nominal operating condition of SMART reactor are estimated as -1.7 and 4.1 %, respectively. For low pressure conditions, it is expected pressures at other axial locations are evaluated with smaller values in MATRA-S.

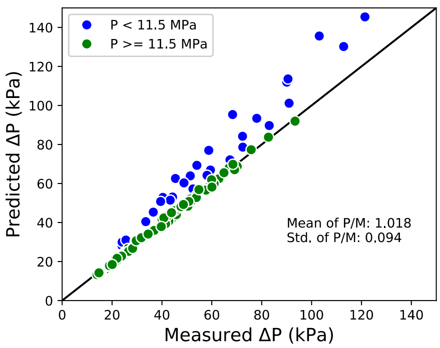

Fig. 6. Comparison between SMART 5×5 bundle pressure data and MATRA-S results (two-phase)

5. Conclusions

Subchannel analysis code, MATRA-S is recently updated to be used in FA and core pressure drop analysis for SMART application. Re-dependent K model and friction factor correlation suggested based on out-pile test results were adopted in this code. Validation results in this study support that MATRA-S is capable of predicting the axial pressure drop distributions and core pressure drop in SMART fuel assembly and reactor core, for both single- and two-phase flow conditions. Best-estimations with ±7% error are achievable for SMART reactor operating conditions and conservative evaluations from thermal design point of view are expected for low pressure conditions when using the modified MATRA-S code.

NOMENCLATURE

A : Flow channel area (m^2)
$\overline{A}$: Mean flow channel area (m^2)
F : Loss term (m^2/kg)
f : Friction factor
f_T : Turbulent momentum factor
g : Gravitational constant (m/s^2)
K : Loss coefficient
$\dot{m}$: Mass flow rate (kg/s)
P : Pressure (Pa)
Re : Reynolds number
U' : Axial momentum velocity (m/s)
W : Lateral cross flow rate per unit axial length (kg/m-s)
w' : Turbulent mixing flow rate per unit axial length (kg/m-s)
x : Fluid quality
Δt : Transient time step (s)
Δx : Axial calculation node length (m)

Greek letters

α : Void fraction
$\phi^2_{2-\phi}$: Two-phase multiplier
θ : Angle between flow direction and gravitational direction (rad)
ρ : Fluid density (kg/m^3)
ρ' : Effective density (kg/m^3)

Subscripts

I, J : Channel index
j : Axial node index

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