EVALUATION OF 1-D VOID AND PRESSURE DROP MODELS OVER A WIDE RANGE OF FUEL BUNDLE GEOMETRIES AND OPERATING CONDITIONS

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ABSTRACT

The accurate prediction of void fraction and two-phase pressure drop in fuel rod bundles is fundamental to the safe operation of the fuel in nuclear power plants and to the assessment of the safety margins with respect to the licensing limits. These predictions directly impact the pump power requirements, the flow distribution within the core, the nuclear feedback (and hence the power distribution) and the margin to the boiling transition, and lift force, safety limits. A typical approach to the void and two-phase pressure drop predictions in fuel safety analysis is the use of a one-dimensional, three-equation, model to calculate the mass flow, momentum and enthalpy distribution within the considered channels. In this approach, the void fraction is calculated using a constitutive model that typically accounts for phase slip and subcooled boiling. The pressure drop results from the momentum equation and requires the use of additional constitutive relations to account for the two-phase effect on the wall friction and local pressure losses. In this work, a large database of fuel bundle void and pressure drop data from Westinghouse (WES) and the open literature was collected. The predictive capabilities of many void and two-phase pressure drop correlations were evaluated with the objective to investigate and identify the models that are robust and accurate over a large range of conditions. The length scale in the subcooled boiling model is shown to have significant impact on the void predictions and should hence be carefully considered. Based on the results, some recommendations for the future development of void and pressure drop correlations are provided.

KEYWORDS
Void, pressure drop, two-phase flow, fuel bundle, optimization

1. INTRODUCTION

The evaporation of the coolant in a nuclear reactor core affects significantly the value of the average coolant void and density. A higher void corresponds to a lower moderation which in turn influences the local neutron flux and thus the local power. Due to the feedback between the local power and the local average density, it is important to predict accurately the local void value in order to predict the correct response of the nuclear reactors cores [1]. The prediction of void is performed by using models predicting

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the energy transfer and the transport of the vapor phase along the system [2]. The void prediction is a required input for computing many key flow parameters. It is important in the modeling of the two-phase flow pattern transitions, heat transfer, pressure drops and thus plays a crucial role in many thermal-hydraulic simulations. Due to its relevance in characterizing two-phase flows, several void correlations have been proposed and assessed in this work by comparing their predictions against experimental data.

Despite being limited to co-current flow, void correlations based on drift-flux model are often recommended considering their simplicity and predictive accuracy. A review of a wide range of void correlations based on the Zuber-Findlay drift-flux model has been conducted and documented in [2], evaluating them against experimental PWR and BWR steady-state and transient (boil-off experiments) data obtained from facilities in France, Japan, Switzerland, the UK and the USA. The large size of the experimental database allowed a detailed statistical analysis that compared the different correlations and has pointed out that the iterative correlations do not increase significantly the accuracy of the prediction [2]. The present work assesses the predictive capability of available void correlations (internal to Westinghouse and from open literature) against a larger experimental database, extends their applicability to the high void region and further investigates on the subcooled boiling region (comparing the models of Levy and EPRI).

The main goal of this work is to review and optimize Westinghouse's methods to compute void fraction and pressure drop in BWR fuel assemblies. In addition, many models available in the literature are assessed to investigate the robustness and prediction capabilities of these models over a wide range of conditions, beyond their original development databases. In preparation of this project a large number of void fraction and pressure drop databases have been collected. In addition to the available internal FRIGG databases, other databases in rod bundle from the open literature have been compiled. The void benchmark analysis has been first conducted in order to select the most recommended void correlation over the relevant range of interest. It is important to accurately predict the void in order to accurately predict the pressure drop. Then, the attention has been moved to the single-phase pressure drop and the derivation of an optimized friction factor. Once the optimal friction factor is known, the grid pressure loss coefficients have been adjusted by minimizing the statistical objective functions such as mean error and standard deviation. A comparison between several two-phase friction multipliers has then been conducted and an optimized correlation has been proposed. Finally, the total pressure drops over the bundle heated length have been computed including the grid two-phase pressure drop where the homogeneous and separated two-phase multipliers have been compared.

2. MODELS DESCRIPTION

Currently, two-phase flows are still widely modeled by using the homogeneous and separated flow approaches, including for BWR core simulator (e.g. POLCA7). In the present work, the following approach has been adopted for the TH steady-state calculations: the conservation equations are based on the homogeneous equilibrium model (under the assumption of thermodynamic equilibrium between the phases that are considered as homogenous mixture). The non-homogeneity and non-equilibrium are accounted by means of empirical constitutive relations (void correlation, subcooled boiling model, two-phase friction multiplier, etc). For practical purposes, a code was specifically developed for this validation, though its core capabilities are essentially equivalent to the TH module of the Westinghouse core simulator POLCA7. Once the inputs have been collected for each experimental run, the code reads the boundary conditions and experimental measurements, performs the steady-state TH calculations (see Sections 2.1 to 2.4) and compares the measurements with the predictions.

2.1. Heat Balance and Void Fraction

The thermodynamic quality, x_e, is computed from steady-state heat balance considerations. The steam quality, x_a, is then calculated using a subcooled boiling model. Finally, the void fraction is computed by means of void correlations from the literature [2] or developed at Westinghouse.

2.2. Void Models

Table I shows that the void correlations have been classified in two groups. The simple homogeneous void model has been considered as a reference. The first group is represented by the slip ratio models based on empirical relationships which compute the slip (S) between the two phases. The second group is given by the drift-flux models which compute the distribution parameter and the drift-flux velocity by using empirical relations.

The drift-flux formulation developed by Zuber and Findlay for the void fraction is given by

$$\alpha = \frac{j_g}{C_0\, j + u_{gj}} \tag{1}$$

where j and j_g are respectively the mixture and vapor superficial velocity, C_0 is the drift-flux distribution parameter that is a covariance coefficient for cross-section distributions of void fraction and total superficial velocity and u_{gj} is the drift-flux velocity defined as cross-section averaged difference between gas velocity and total superficial velocity [1]. Hence this model is able to take into account both the vapor production and the effect of the relative velocity between the two phases included respectively in j_g and u_{gj} [2].

Table I: Void correlations

Homogeneous:	$\alpha = \frac{\frac{x_a}{\rho_g}}{\frac{(1-x_a)}{\rho_l}+\frac{x_a}{\rho_g}}$	[1]
Slip:	$\alpha = \frac{\frac{x_a}{\rho_g}}{\frac{(1-x_a)}{\rho_l}S+\frac{x_a}{\rho_g}}$	[1]
	Smith SCP	[3] WES
Drift-Flux:	$\alpha = \frac{j_g}{C_0 j+u_{gj}}$	[1]
	Zuber-Findlay (Z-F), Bestion, Chexal, EPRI Toshiba, Inoue, Maier-Coddington (M-C) AA69, AA78	[2] WES

2.3. Pressure Drop

The total axial pressure loss for the two-phase mixture in a channel along the flow direction can be split into four main contributions (gravity, friction, local flow obstructions and acceleration) as:

$$\left(\frac{dp}{dz}\right)_{total} = \left(\frac{dp}{dz}\right)_G + \left(\frac{dp}{dz}\right)_F + \left(\frac{dp}{dz}\right)_K + \left(\frac{dp}{dz}\right)_A \tag{2}$$

2.3.1. Gravitational pressure loss

Assuming the gravity as the only external volume force, the gravitational contribution is expressed as

$$\left(\frac{dp}{dz}\right)_G = \rho_m\, g \tag{3}$$

where the mixture density ρ_m is defined as [1]

$$\rho_m = (1-\alpha)\rho_l + \alpha\, \rho_v \tag{4}$$

2.3.2. Frictional pressure drop

A common approach used to predict the two-phase pressure drop is to first compute the single-phase liquid pressure drop assuming that the two-phase mixture is entirely in the liquid phase and then to multiply it by the two-phase pressure drop multiplier ϕ_{F0}^2 as [1]

$$\left(\frac{dp}{dz}\right)_F = \phi_{F0}^2 \left(\frac{dp}{dz}\right)_{F0} \tag{5}$$

where the pressure loss for the single-phase liquid is given by [1]

$$\left(\frac{dp}{dz}\right)_{F0} = \frac{f}{D_W}\frac{G^2}{2\,\rho_l} \tag{6}$$

All the friction factors (*f*) and two-phase friction multiplier correlations are documented in [4] except for the Westinghouse correlations that are proprietary.

2.3.3. Local pressure loss

The local pressure loss is due to a local geometric obstruction within the fluid flow region around a grid or an orifice. In single-phase it is computed as [1]

$$\left(\frac{dp}{dz}\right)_{K0} = \varepsilon\,\frac{\rho_l\, u^2}{2} = \varepsilon\,\frac{W^2}{2\,\rho_l} \tag{7}$$

where ε is the pressure loss coefficient for the local perturbation.
The two-phase local pressure loss is calculated by using a two-phase spacer multiplier ϕ_{K0}^2

$$\left(\frac{dp}{dz}\right)_K = \phi_{K0}^2 \left(\frac{dp}{dz}\right)_{K0} \tag{8}$$

The two-phase local multipliers used are derived from the homogeneous [1] or separated [5] flow models and are respectively defined as:

$$\phi_{K0,homo}^2 = \left[1 + x_a\left(\frac{\rho_l}{\rho_g} - 1\right)\right] \tag{9}$$

$$\phi_{K0,separ}^2 = \frac{(1-x_a)^2}{(1-\alpha)} + \frac{\rho_l}{\rho_g}\frac{x_a^2}{\alpha} \tag{10}$$

2.3.4. Acceleration pressure drop

Considering the flow incompressible, the flow changes velocity in a channel due to phase change and/or area change. The acceleration pressure contribution is due to the flow acceleration that affects the amount of net momentum in and out of the considered fluid volume. The contribution due to the phase change is computed as [1]

$$\left(\frac{dp}{dz}\right)_{A,PhCh} = \frac{d}{dz}\left(G^2\, \phi^2_{A0,PhCh}\right) \tag{11}$$

where $\phi^2_{A0,PhCh}$ is the phase change acceleration two-phase multiplier [1]

$$\phi^2_{A0,PhCh} = \frac{(1-x_a)^2}{\rho_{ls}\,(1-\alpha)} + \frac{x_a^2}{\rho_{gs}\alpha} \tag{12}$$

The acceleration contribution due to the area change (sharp expansion or sudden contraction) is computed as [5]:

$$(\Delta p)_{A,ArCh} = \varepsilon_{ArCh}\frac{G^2}{2\,\rho_l}\phi^2_{A0,ArCh} \tag{13}$$

where $\phi^2_{A0,ArCh}$ is the area change acceleration two-phase multiplier. The reversible and irreversible pressure losses due to the area change (ε_{ArCh}) are documented in [5].

2.4. Subcooled boiling

Although the bulk boiling is prevalent in the thermal-hydraulics performance of BWR reactors, accurate models are required to predict the void in the subcooled region. The mechanistic (EPRI model [6]) and profile-fit (Levy's model [3]) approaches have been analyzed in order to predict the forced convection subcooled void fraction. The former postulates a phenomenological description of the boiling heat transfer process and so computes the subcooled flow quality and void fraction, the latter postulates a convenient mathematical fit to the data for the flow quality between the void departure point z_d and the point at which thermodynamic equilibrium is reached z_e as [7]

$$x_a = x_e - x_{e,d}\left(exp\left(\frac{x_e}{x_{e,d}}\right) - 1\right) \tag{14}$$

3. VALIDATION DATABASES

3.1. Void Data

A wide range of experimental void fraction data (internal and external to Westinghouse) in rod bundles at various pressure and mass flux has been collected and provides the opportunity to assess the predictive capability and the overall applicability of the void correlations (internal and external to Westinghouse). The data covers pressure from 0.1 MPa to 16.9 MPa and mass fluxes from 2.8 kg/m^2/s to 4138.9 kg/m^2/s and provides information on void fractions in sub-channels and rod bundles. This includes BWR, PWR and RBMK normal operating conditions and small and large break transient conditions. The experimental data can be split in 3 different groups according to the type of the experiment performed and are labeled as steady-state, boil-up and boil-down experiments. The majority of the experiments were performed under steady-state conditions with inlet sub-cooling, mass flux and power at constant values. Figure 1 provides an indication of the wide range of pressure and mass fluxes covered by the experimental data.

Of particular interest, Westinghouse void databases of modern BWR fuel design (namely SF24VA and SF24VB) have been considered for the void analysis. The main difference between the two databases is that SF24VB fuel design contains part-length rods. The external database is similar to the database collected in [2] by PSI with the addition of the BFBT [9] and PSBT [10] void databases. Information about the operating conditions and geometry of the experimental databases is summarized in [8].

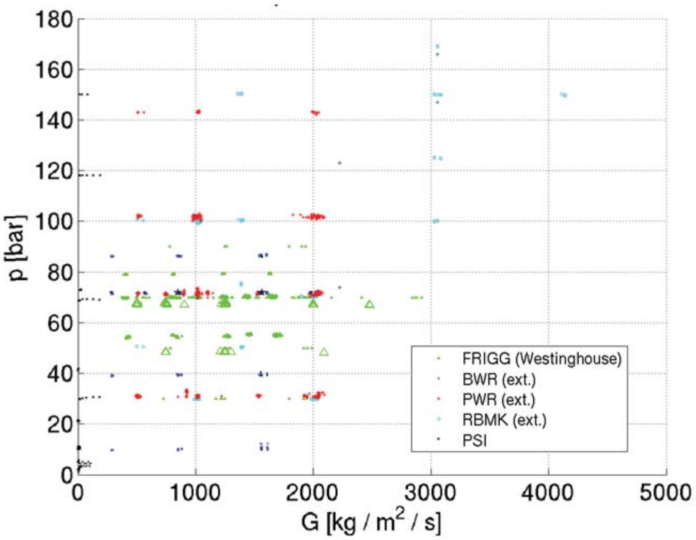


Figure 1. Pressure and mass flux range of the void database

3.2. Pressure Drop Data

A wide range of experimental pressure drop single and two-phase data (internal and external) at various pressure and mass flux has been collected and provides the opportunity to assess the predictive capability and the overall applicability of the pressure drop correlations (internal and external to Westinghouse). The data covers pressure from 0.2 MPa to 8.6 MPa and mass fluxes from 291 kg/m^2/s to 2560 kg/m^2/s and provides information on pressure drops in BWR fuel bundles. Information about the operating conditions and geometry of the experimental databases is summarized in [8].

4. RESULTS

4.1. Comparison with Void Data

4.1.1. Whole range

The experimental data have been used to assess the predictive capability of various void correlations used in thermal-hydraulic analysis codes. In order to determine the quality of the predictions for each experimental run, the absolute error has been computed as the difference between the measured and predicted value

$$err = \alpha_{meas} - \alpha_{pred} \tag{15}$$

The comparison between the void correlations is based on the mean absolute error and the standard deviation. The simulations have first been run by using a "reference" model (Levy subcooled boiling model with equivalent wetted diameter and 50 axial nodes along the channel grid). The statistical analysis has been performed mainly using the Westinghouse void databases SF24VA and SF24VB (more details are given in [8]). Figure 2 shows the void mean error and the void standard deviation over the whole void range. As expected, the homogeneous model over-predicts the measurements [1]. The original Zuber-Findlay model does not give good results when it is applied over the entire void range because of its limitation in the high void region. The iterative void correlations, such as EPRI and Chexal, increase the complexity of the void model without giving a dramatic increase in the quality of the prediction. Bestion (one of the simplest model tested) and AA78 have a low mean error. Regarding the standard deviation, the unreliable behavior of the homogeneous model is confirmed. The AA69, Bestion, AA78, SCP, Toshiba, Maier-Coddington and Inoue give good results. Figure 3 show the values predicted by the void correlations versus the measured values for the databases SF24VA and SF24VB. It shows a quite generic under-prediction of the void in the subcooled region and a deviation for some correlations towards higher void fractions.

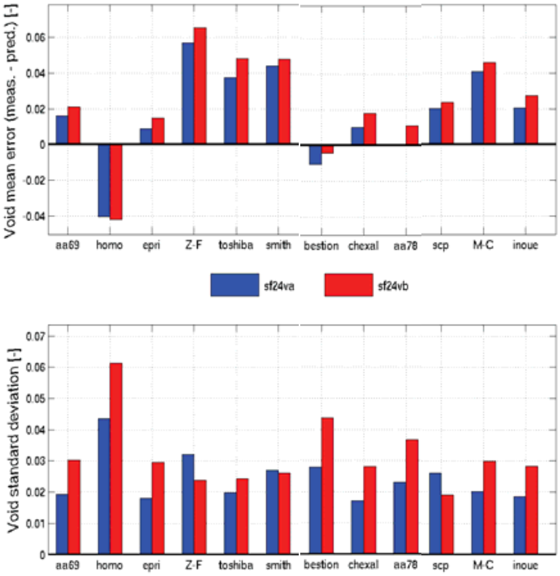
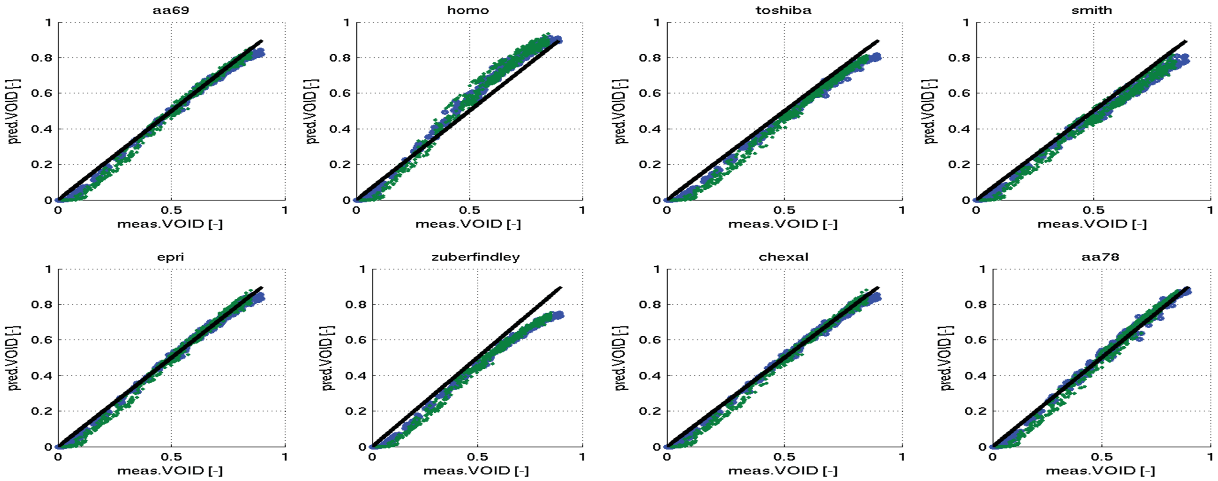


Figure 2. Void mean error and standard deviation for SF24VA and SF24VB databases



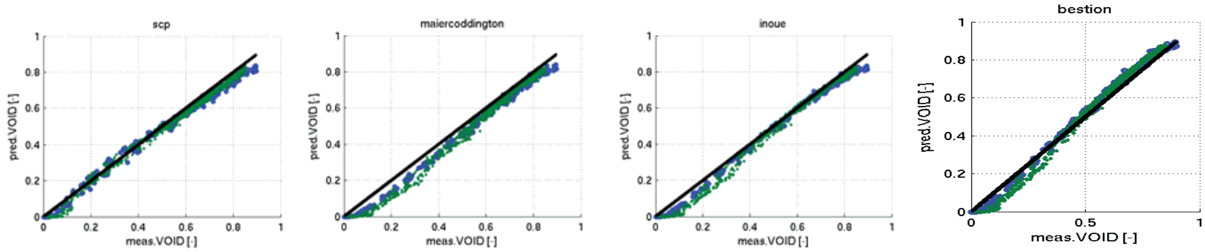


Figure 3. Void predicted vs. measured for SF24VA (blue) and SF24VB (green) databases

Other void databases applicable to BWR, PWR, RBMK rod bundles and single channels have been analyzed statistically (more details are documented in [8]). Bestion, Maier-Coddington, Inoue, EPRI, Chexal, AA78, AA69, SCP and the iterative correlations show good statistic behavior. As expected, some limitations were identified outside the application range of the correlations. In particular, AA69, AA78, SCP and Smith correlations are limited to BWR fuel operating conditions.

4.1.2. Subcooled boiling region

After assessing the predictive capability of the void correlations over the entire range of steady-state data, the attention has been focused on the subcooled boiling region in order to investigate the under-prediction pointed out previously. An issue regarding the application of subcooled boiling models to fuel bundle geometry is the relevant characteristic length to be used in the Nusselt number. Figure 4 shows the deviation between predicted and measured values in the subcooled boiling region by using a characteristic length equal to the wetted (D_W) and heated (D_H) diameter for both the Levy and EPRI subcooled boiling models. For the databases SF24VA and SF24VB it seems that the use of the heated diameter as characteristic length gives significantly better predictions.

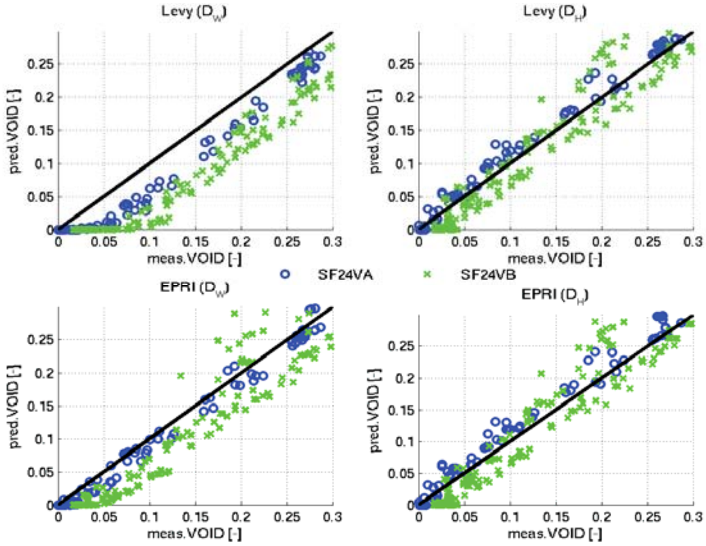


Figure 4. Void predicted vs. measured for SF24VA (blue) and SF24VB (green) databases

The relevant characteristic length to be used in subcooled boiling models has been further investigated considering the PSBT [10] void database which yields a significant variation in heated diameter (details are documented in [8]). However, it is not conclusive that the heated diameter should generally be used as characteristic length. Further studies are needed.

4.1.3. High void region

One of the important objectives of this work was to confirm the predictive applicability of void correlations in the very high void region. Due to the lack of experimental data in this region, the analysis has been performed as follows. Boundary conditions leading to void fraction up to unity have been arbitrarily generated and the void fraction was predicted by all considered correlations. Using the void predicted by the homogeneous model as reference it has been shown that most, but not all, predictions reach unity. Moreover, comparing the correlations with the predictions based on a given slip ratio, it has been shown that most of them are located within a reasonable slip ratio (between 2 to 3). This investigation is documented in details in [8]

4.1.4. Recommended void correlations

Some recommendations for LWR core applications can be drawn from the statistical analysis performed over the entire range of experimental data and the analysis in the high void region. The void correlations AA69, AA78, Smith, Toshiba, SCP, Maier-Coddington and Inoue yield good statistical results, close to the performance of the iterative correlations (EPRI, Chexal) and sometimes better. Figure 3 points out possible deviation towards higher void fraction [0.8 - 0.9] but further analysis (Section 4.1.3) demonstrate a reasonable behavior in that region, except for Maier-Coddington, Inoue and Toshiba void correlations. Bestion void correlation, despite its relative simplicity, also shows a good potential which could be improved by further optimizing the correlation.

4.2. Comparison with Pressure Drop Data

Available pressure drop data in fuel bundle have been collected and used to validate the considered pressure drop models (section 2.3). Note however that the pressure drop models include some empirical parameters that depend on the considered bundle geometry, in particular with respect to the wall roughness (friction factor) and spacer grid design (local loss coefficient). Hence these two parameters need to be first carefully considered when performing a fuel bundle pressure drop calculation.

4.2.1 Single phase data

4.2.1.1. Friction factor

The attention has been focused on the single-phase pressure drop databases which have sufficiently detailed measurements to allow removing the local grid contribution from the measured pressure drops. It is hence possible to directly adjust the friction factor so that the predicted frictional pressure drops match the experimental ones. A multi-objective non-linear constrained optimization has been performed in order to minimize both the mean error and the standard deviation by using the BFBT [9] single-phase database. The locations of the pressure measurements are depicted in Figure 5. In particular, the pressure taps T3-T1 and T4-T2 have been used to avoid any local pressure losses due to the spacer grids.

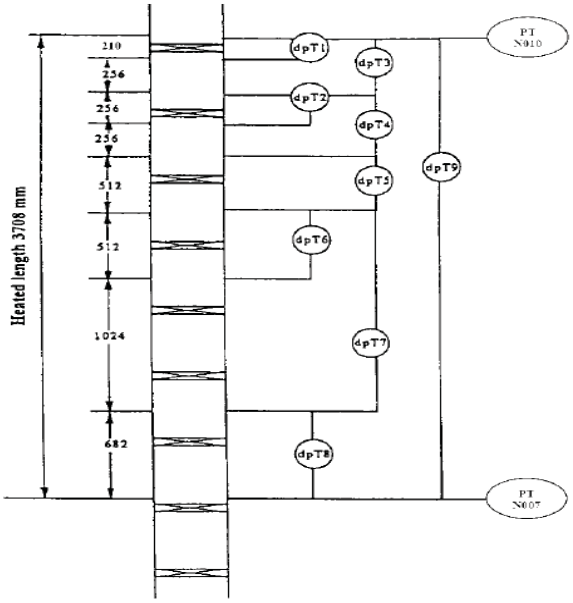


Figure 5. BFBT test bundle with pressure tap elevations

It is proposed to optimize a friction factor correlation under the form

$$f = \frac{a}{Re^b} \tag{16}$$

By using the goal attainment method SQP the coefficients *a* and *b* were found equal to 0.303 and 0.252, respectively. Figure 6 depicts the statistical analysis performed for the databases BFBT by computing the mean error and the standard deviation when different friction factor correlations are used, including the proposed correlation called “optimum”. The optimization has tried to minimize both objective functions, achieving a trade-off. The Moody correlation yields the lowest mean error, but the optimum correlation has the lowest standard deviation, equal to 4.46e-4 bar.

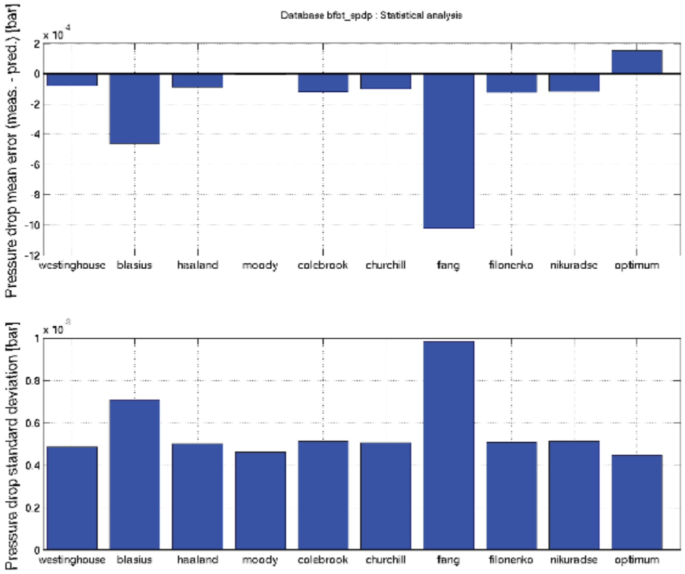


Figure 6. BFBT single-phase friction pressure drop mean errors and standard deviations

In this simulation, it can be again observed that the iterative correlations (Colebrook and Nikuradse [1]) increase the complexity of the solution without providing significant prediction improvement.

When performing the same analysis using other available databases, the proposed "optimum" correlation gave the lowest mean error and standard deviation, as documented in [8].

4.2.1.2. Grid pressure loss coefficients

Once the optimal friction factor has been found, grid pressure loss coefficients have been calculated by performing the same optimization as for the friction factor. It is important to underline that only single-phase data from measurements at 200 ˚C have been used to develop the single-phase spacer loss correlations since they are the most representative, as compared to reactor conditions. It is proposed to optimize the grid loss coefficient correlation under the form

$$\varepsilon = \frac{a}{Re^{b}}$$

Results of several optimizations for various grid designs are documented in [8]. In general, the proposed grid loss coefficient model provides a very good fit to the experimental data.

4.2.2. Two-phase data

4.2.2.1. Two-phase friction multiplier

The attention has been focused on the two-phase pressure drop databases which contain sufficient measurements to allow removing the grid pressure drop from the measured pressure drop. It is hence possible to compare the predicted two-phase pressure drops, including only friction and acceleration due to phase change, against the experimental measurements. The simulations have been run with the AA69 void correlation, the Levy subcooled boiling model (with equivalent heated diameter) and the optimum friction factor. A multi-objective non-linear constrained optimization has been performed in order to minimize both the mean error and the standard deviation calculated from the available databases.

A two-phase friction multiplier was optimized, using the base form of the (proprietary) AA69 two-phase friction multiplier, by using the goal attainment method SQP. Figure 7 depicts the statistical analysis performed for the Westinghouse database SF24EC where the mean error and the standard deviation from different friction two-phase multiplier correlations are used, included the proposed optimized correlation (AA69OPT) that yields the best performances, as expected. Figure 8 shows the measured against predicted two-phase friction pressure drops. Most of the two-phase friction multipliers, except Cavallini and Chen correlations [4] that present the biggest deviations by under- and over-predicting respectively the data, provide reasonable results. In general, as slight under-prediction of the two-phase pressure drop data can be observed.

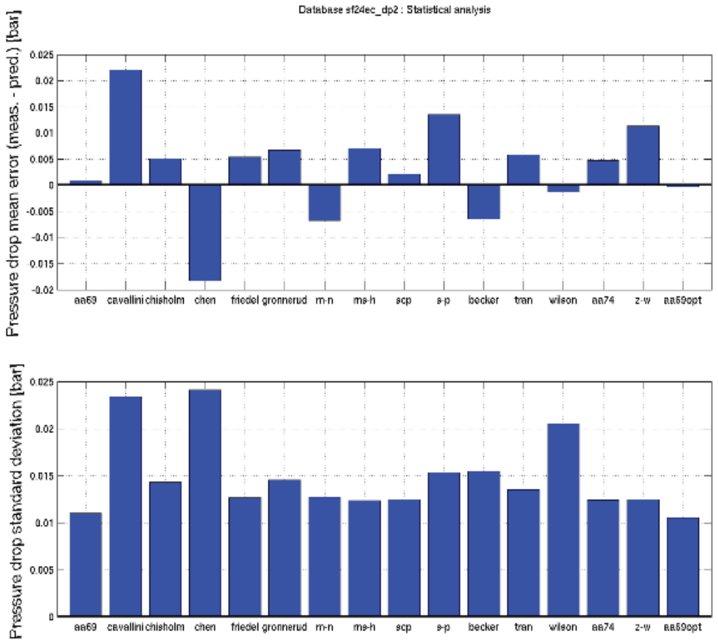


Figure 7. SF24EC two-phase friction pressure drop mean errors and standard deviations

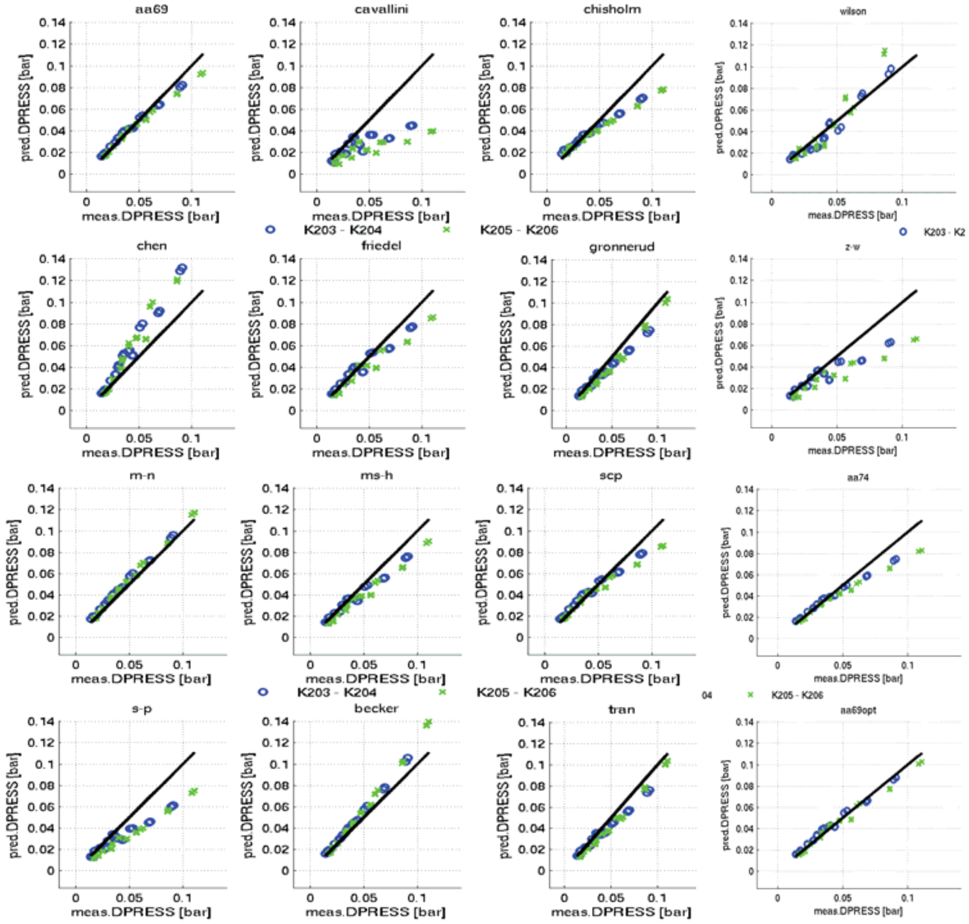


Figure 8. Two-phase friction pressure predicted vs. measured for SF24EC database

4.2.2.2. Two-phase grid multipliers

Once the friction pressure drop has been optimized (friction factor and two-phase multiplier), the two-phase databases, for which the single-phase grid pressure loss coefficients have been adjusted for (see Section 4.2.1.2), have been considered. The grid two-phase multipliers derived from the homogeneous and separated flow models (section 2.3.3) were both considered. Figure 9 depicts the predicted vs. measured total pressure drop for several databases (BFBT and Westinghouse). It can be observed that the homogeneous model is better suited to predict the local two-phase pressure drop, as compared to the separated flow model. Some improvements could be made at high pressure drops.

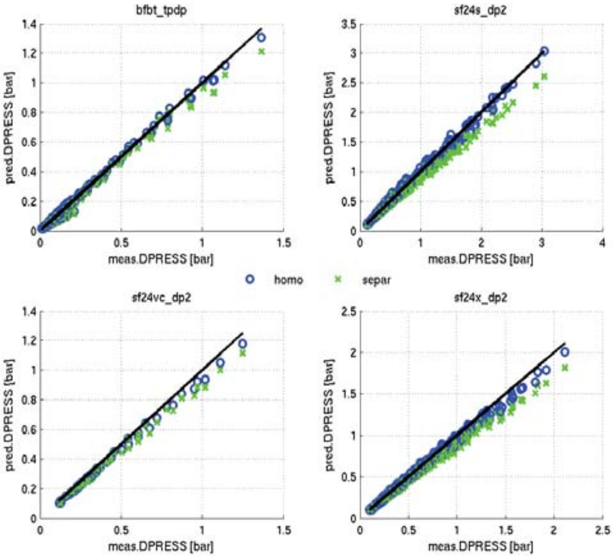


Figure 9. Predicted vs. Measured two-phase pressure drop for several databases using the homogeneous (blue) and separated flow (green) two-phase local multiplier

5. CONCLUSIONS

A survey and an assessment of void fraction and pressure drop correlations in rod bundles have been performed. From the results given by the statistical evaluations of the various void correlations it has been observed that:

1. Bestion, Chexal and EPRI provide robust void prediction over the whole range of considered conditions
2. Good performance of AA69, AA78, SCP and Smith correlations has been confirmed for BWR fuel operating conditions
3. Maier-Coddington, Inoue and Toshiba have shown a good statistical performance even when tested with the boil-off experimental data, but yield a questionable behavior in the very high void region
4. The characteristic length to be used in a subcooled boiling model (as part of the Nusselt number) is not necessarily equal to the hydraulic or heated diameter. Further investigations are recommended

Concerning the pressure drop evaluation, the following conclusions have been drawn:

1. An optimized explicit friction factor correlation depending only on empirical coefficients and the Reynolds number has been proposed using the BFBT database. Even though it does not depend on the surface roughness, the proposed model predicts well the friction pressure drop from other available databases.
2. A single-phase local loss coefficient depending only on empirical coefficients and the Reynolds number is well suited to account for the grid effect for all considered single-phase pressure drop databases
3. Most of the available correlations for the two-phase friction multiplier present reasonable predictions. However, an optimized correlation is proposed based on the available data.
4. The grid two-phase multiplier derived from the homogeneous flow model is recommended for predicting the grid two-phase pressure drop. Some improvements could be made at high pressure drops.

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