ORFEO^{TM} – A CHF CORRELATION FORM APPLIED TO GAIA, AREVA's ADVANCED PWR FUEL ASSEMBLY DESIGN

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ABSTRACT

The ability to properly and confidently predict the critical heat flux (CHF) for a PWR fuel assembly design in safety analysis applications is a regulatory requirement. Since the complexity of the physical phenomenon still poses significant challenges in regard to a fully mechanistic description of the CHF, semi-empirical models based on extensive and representative testing have to be utilized.

Over the last two years, AREVA has performed CHF testing for the GAIA fuel assembly design at its Karlstein Thermal Hydraulic test facility (KATHY) in Karlstein, Germany. These tests reflect expanded ranges of thermal-hydraulic parameters in order to reduce the dependence of correlation extrapolation to untested conditions. This leads to increased confidence in the application of the predicted GAIA CHF performance. In addition, AREVA has made significant progress in developing ORFEO^{TM}, an advanced CHF correlation form for PWR fuel assemblies.

The paper discusses key elements that emphasize the robustness of the ORFEO^{TM} CHF correlation form. This includes the modular approach consisting of three terms (each of them having a unique, well defined function) and the accommodation of two key elements: (i) the introduction of the "burnout length" parameter and, (ii) the avoidance of the "heated length" parameter. The improvement in the description of the equilibrium quality dependency at an extended range provided by the "burnout length" parameter is presented. Additionally, the analysis results that led to the avoidance of the "heated length" parameter are discussed.

The paper also presents relevant results regarding the application of the ORFEO^{TM} correlation form to the GAIA CHF test database.

KEYWORDS
GAIA, CHF, ORFEO^{TM}, correlation

1. INTRODUCTION

The development of the GAIA fuel assembly design [1] by AREVA has been complemented with extensive CHF testing and research into an improved correlation representation (ORFEO^{TM} correlation form) which reflects the selection of terms based on their effectiveness to represent the measured CHF performance as well as in interpolated states and limited, but validated, extrapolated states. The GAIA fuel design will have a fuel design-specific CHF correlation based on the ORFEO^{TM} correlation form that will be discussed in Section 6.

An important phenomenon in the heat transfer process from the fuel rod to the coolant of a reactor core is the occurrence of the boiling crisis [2]. The nuclear industry has relied upon the critical heat flux (CHF) or dryout correlation tool as the primary tool for assuring the required protection against the boiling crisis condition is accurately captured in numerical simulations of any light water reactor core's operation in accordance with regulatory requirements. The correlation tool is dependent on the thermal-hydraulic (subchannel) code's local coolant conditions predictions of a tested state to associate the measured CHF state to a combination of geometric characteristics of the fuel design with the predicted local coolant conditions. Therefore, it is important that a CHF correlation rely on (i) an accurate measurement of the thermal performance of a fuel design, (ii) a sufficient range of tested conditions that adequately cover the planned correlation application range, (iii) adequate technical validation to address the regions where predicted interpolation and extrapolated CHF performance is used. For several years, AREVA has pursued these key aspects of the CHF correlation basis and formulation and has implemented them in the support of the GAIA PWR fuel assembly design which will be utilizing the ORFEO^{TM} correlation form in batch production.

AREVA has been particularly active during the last decade performing PWR and BWR CHF tests at its Karlstein Thermal Hydraulic test facility (KATHY) [3]. These tests were performed for a large variety of fuel designs besides GAIA and include the HTP^{TM}, AFA 2G™/AFA 3G™, ATRIUM™ 10, and ATRIUM™ 11 design families as well as other designs. Several of these tests, and specifically for those supporting the GAIA fuel design, reflect expanded ranges of tested flow conditions and axial power shapes to achieve a more thorough understanding of the fuel design's thermal capabilities. The benefit of this large multi-fuel design database in the ORFEO^{TM} correlation form will be discussed later in Section 6.

During this same time period, AREVA licensed four new CHF correlations and has several others in the licensing process in support of its new and upgraded PWR and BWR products. AREVA has compiled unique experience in correlation development that has been incorporated into the correlation for GAIA development process to strengthen the technical defense for the application of the correlation in licensing analyses.

This process, which is above the current state-of-the-art practices, is described in [4]. The key elements, which have been found to be necessary to ensure a safe, reliable, and robust correlation for nuclear safety analyses are:

- high quality and reliable CHF testing,
- a sufficient coverage of the application domain to justify an extended correlation application range, including a strong technical basis for interpolations and extrapolations,
- key parameters identified in an extensive analysis of the database of CHF measurements,
- a robust methodology/process for developing and validating correlations, and

- the use of physical elements within the usual purely empirical correlation form.

2. CORRELATION DEVELOPMENT PROCESS

AREVA's CHF correlation development process described in [4] is illustrated in Figure 1 with its four stages.

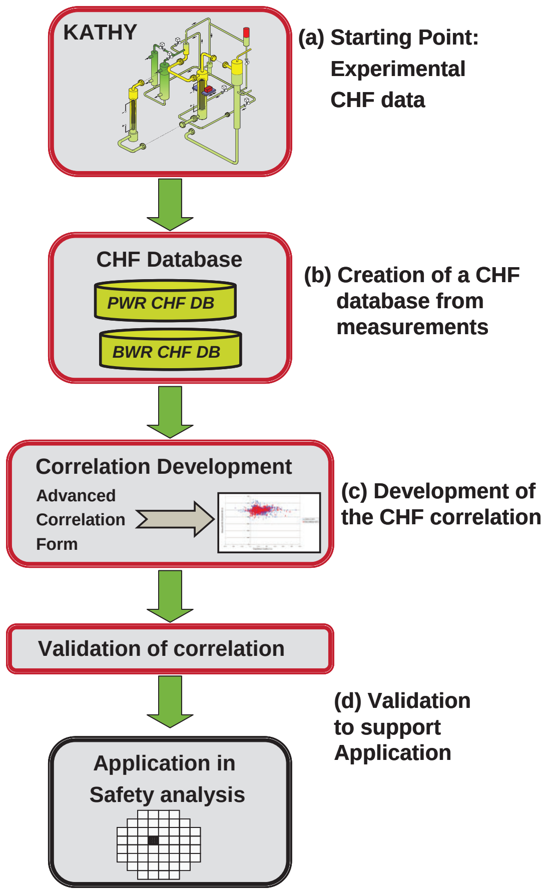


Figure 1. AREVA's advanced CHF correlation development process

AREVA's CHF correlation development process is characterized by:

1. An extensive database obtained from several CHF test facilities and for numerous fuel designs covering a broad range of flow conditions, axial power shapes as well as geometrical parameters provide the means for a robust determination of dependencies of the critical heat flux on pressure, mass flux and quality as well as geometrical influences.
2. An advanced correlation functionality that incorporates, in addition to some standard empirical terms, more physically based terms that reflect the transition of flow regimes. These terms are based also on the local flow conditions.
3. Advanced fitting algorithms such as genetic algorithms [5] and robust fitting schemes. These tools efficiently provide a more reliable representation of the data compared to the standard least square fitting method. The optimization of the CHF correlation involves both,

- finding the most appropriate mathematical function i.e. the empirical terms of the CHF correlation, and
- the coefficients of both, the empirical and the physically based terms.

4. An extensive set of verification and validation methods. These methods are required to ensure high quality standards of the CHF correlation. These methods include the detailed statistical analysis of the CHF correlation based on its underlying CHF test data as well as a representative test matrix of subchannel code local conditions covering the range of PWR core design analysis. Also included in the validation is the close examination of the CHF correlation in application to better understand the behavior of the predicted CHF as a function of elevation and what contributing factors are influencing the behavior.

The entire process continues to be based upon the thermal-hydraulic subchannel code COBRA-FLX™ [6], part of AREVA's ARCADIA® code system for core design and safety analysis [7] and the experience and expertise within AREVA.

3. CHF MEASUREMENTS AT KATHY

The first prerequisite in assessing the safety margin regarding CHF is to obtain a set of high quality CHF measurements. The conditions of these measurements should represent the range of conditions expected in the reactor core during normal, upset and accidental conditions. The common approach is to use a bundle geometry representing the specific features of the fuel assembly design for which the correlation is being developed. Uniform and non-uniform axial power shapes are tested to acquire specific CHF performance characterization that will be utilized in the correlation development.

In order to conduct these measurements, AREVA maintains its own multifunctional KATHY loop at the AREVA Technical Center in Karlstein, Germany [3] [8]. Figure 2 shows an illustrated view of the loop and its hardware accommodation for PWR and BWR testing. Besides possessing the capability for full scale BWR and full length PWR CHF testing, it has the capability for obtaining the following:

- Single phase pressure drop measurements on PWR and BWR fuel assemblies (for friction and form losses) and on BWR core components (lower and upper tie plates)
- Adiabatic two-phase flow pressure drop measurements in test bundles
- Void fraction measurement with gamma ray densitometer
- Simulation of reactor transients on BWR fuel assemblies
- Hydraulic instability measurements on BWR fuel assemblies at natural circulation condition

The facility began operation in 1986 for obtaining BWR measurements and has undergone an extended qualification for PWR CHF measurements through extensive benchmarks in 2002-2003 by comparisons, to the formerly used test loops at OMEGA (Grenoble, France) and the CU HTRF (Columbia University, USA) [8].

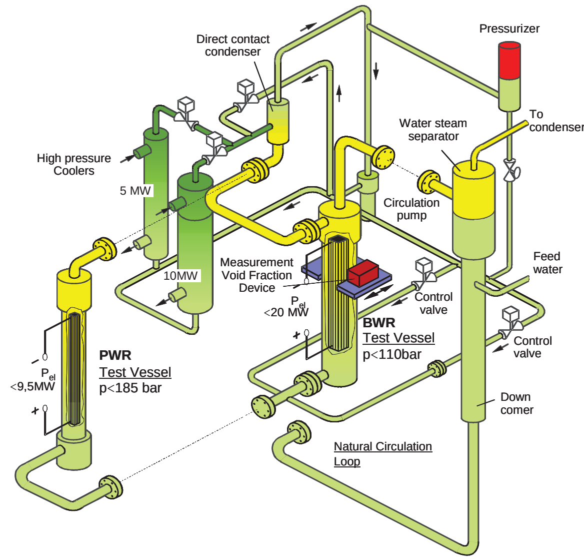


Figure 2. Test loop KATHY

4. ACQUISITION OF CHF DATA SUPPORTING THE CORRELATION FOR GAIA

The second step in the AREVA development process used for GAIA, the creation of a database of measurements, allows further processing of the measurements, as well as the use of a quality assurance process to qualify the measured data on various characteristics. Automation tools have been developed to assess and evaluate the information stored in the database, creating an extensive knowledge base on CHF behavior of fuel assembly designs. This, in turn, provides easy access to test-based observations in answering specific questions on the CHF performance of the GAIA fuel assembly design or any other fuel designs.

AREVA's total PWR database includes measurements from approximately 18,000 data points covering testing of a broad variety of fuel designs (GAIA, HTP™, Mark-BW, Mark-B, Mark-C, and AFA 2G™/AFA 3G™) and a wide range of parameters. Note that the database includes not only measurements from the KATHY loop but also from all the formerly used loops of OMEGA, CU HTRF, UKAEA Winfrith and the Alliance Research Center. The extensive benchmarks [8] performed have ensured the data compatibility within this database. This database contains a wide range of spacer grid designs besides the GAIA grid and its Intermediate GAIA Mixing (IGM) grid such as HTP™ and its respective Intermediate Flow Mixer (IFM), AFA 2G™/AFA 3G™, Mark-BW and its Mid-Span Mixing Grid (MSMG), FOCUS™ and standard split vane grids used for a broad range of fuel assembly geometries (17x17, 18x18, 15x15, etc.).

The CHF test program for the GAIA CHF correlation was carefully defined to:

- cover the geometry range of the initial product offering
- include various axial power shapes
- cover the reasonably attainable range of local conditions that would be used for the correlation application
- provide the detectability of separate effects
- provide a sufficient quantity and coverage in test points for the correlation development and validation databases

Figure 3 identifies the CHF test program supporting the GAIA correlation development. Paired tests are labeled that have allowed the determination of the sensitivity of separate effects. In addition to this CHF test program, extensive CHF testing was earlier performed during the multi-staged development of the GAIA spacer grid to understand the impact of various grid features.

CHF Test	Active Fuel Length (AFL) (ft)	Axial Power Shape (APS)	Cell (Subchannel) Type	Intermediate GAIA Mixer (IGM)	Distance to Grid (dg)	Grid Spacing (gsp)
A	12	uniform	guide tube	no	full	Standard
B	12	cosine	unit (typical)	no		Standard
C	12	cosine	guide tube	no		Standard
D	14	uniform	guide tube	no	full	Standard
E	12	uniform	guide tube	yes	full	N/A
F	12	uniform	guide tube	no	half	Standard
G	14	uniform	guide tube	no	full	Smaller
H	12	cosine	guide tube	yes		N/A
I	14	cosine	unit (typical)	no		Standard
J	14	upskewed	unit (typical)	no		Standard

Figure 3. Breadth of GAIA CHF testing to acquire separate effects

The more important aspect of this GAIA database is the combinations of pressure, mass flux, and quality acquired through testing. Particularly important are the combinations of high quality and high pressure noted [4] earlier by AREVA. Figure 4 provides an example where the high quality/high pressure region is shown as the "extended range". AREVA has made large strides in attaining measurements in this extended region to be better able to:

- develop more robust correlations in the core application range, and
- improve the extrapolation to cover conditions encountered in today's core analysis methods.

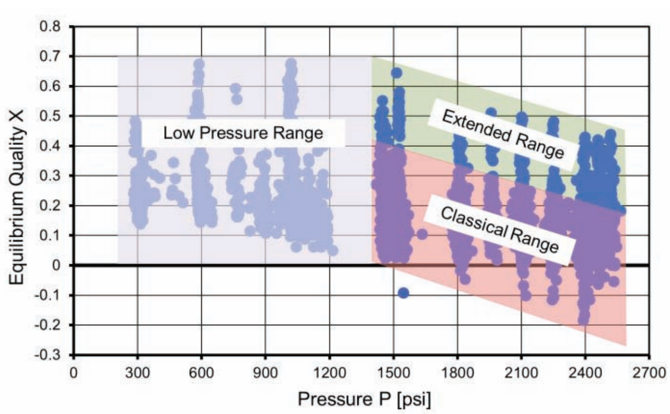


Figure 4. Location of extended range of covered pressures and qualities

The comprehensive nature of the GAIA CHF database provides a strong foundation for the CHF correlation development and the identification of the key dependencies that need to be considered by the ORFEO^{TM} correlation form.

5. FACTORS OF INFLUENCE ON CHF IN ROD BUNDLE GEOMETRIES CAPTURED FOR GAIA

A fully mechanistic description of the boiling crisis phenomenon in a correlation form is still not available. Therefore, AREVA continues to use empirical correlations to determine the CHF performance of fuel designs, including the GAIA fuel design. The successful development of empirical correlations includes the adequate identification of CHF dependencies such that the correlation has fidelity for mapping measured performance to the larger application range. The GAIA CHF correlation is based on flow conditions calculated by a subchannel code (COBRA-FLX™) at the location of departure from nucleate boiling (DNB). Two categories of key dependencies were used:

- local flow conditions (pressure, mass flux and quality)
- radial and axial geometry (rod diameters, grid spans, etc.)

Not all combinations of local flow condition dependencies were directly accessible in the GAIA CHF tests, although they may be desired for developing the CHF correlation. Due to this physical limitation, the GAIA CHF correlation will rely on limited extrapolation that will be validated.

As outlined in Section 4 a large database of CHF measurements across numerous fuel designs has been acquired, including GAIA, to identify the key elements that need to be considered in a CHF correlation. Among the dependencies on local flow conditions, quality has proven to be the most important parameter by AREVA. The dependency on quality has to reflect the transition between different flow regimes, including a transition between DNB and dryout. The often used linear relationship between CHF and equilibrium quality can only be justified within a restricted range.

Therefore, AREVA has introduced the burnout length parameter that physically models the transition between DNB (linear form) and dryout (exponential form) via a smooth function for a large range of qualities. The burnout length is defined as length between the point where a certain predefined threshold in quality is exceeded and the location of DNB occurrence, as illustrated in Figure 5.

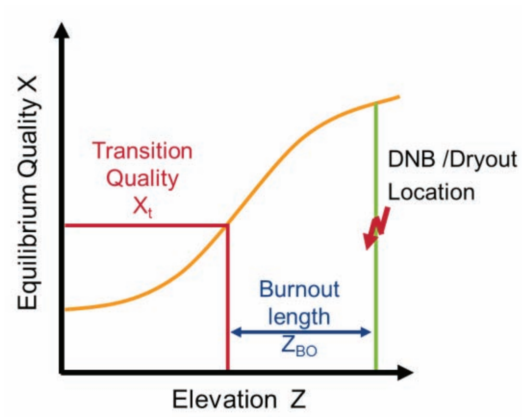
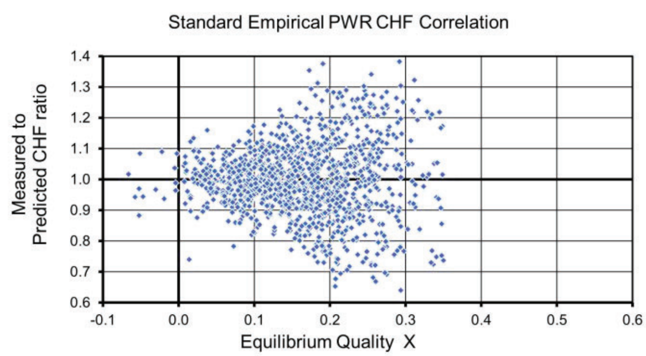


Figure 5. Burnout length definition

This quantity takes into account the impact of the axial heat flux on the local quality and is similar to boiling length used by some dryout correlations for BWR applications [9]. The introduction of the burnout length parameter leads to a significant improvement of the description of the quality dependency at an extended range, as shown in Figure 6. An example of the benefit of the burnout length parameter is provided in Figures 6 (a) and (b), which show the "Measured to Predicted CHF ratio" for a standard empirical PWR CHF correlation and the ORFEO™ correlation form by AREVA, respectively. The standard empirical correlation features a linear-type dependency of CHF relative to the equilibrium quality. For this example, each of these two CHF correlation forms (standard empirical and ORFEO™) was fitted to the same CHF test database (a specific grid design, not GAIA) and then the "Measured to Predicted CHF ratios" were computed. This demonstrates the tremendous reduction in variability on equilibrium quality and subsequently on measured-to-predicted standard deviation provided by the ORFEO™ correlation form. The ORFEO™ correlation form used for the GAIA CHF correlation provides a similar benefit in reduced variability.

(a)



(b)

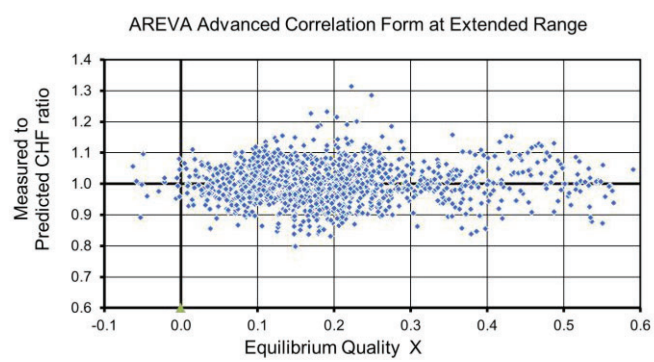


Figure 6. Effect of burnout length: (a) Standard empirical PWR CHF correlation and (b) AREVA's ORFEO™ correlation form with extended quality range

Classical empirical PWR CHF correlations treat fuel assembly types using geometry parameters like:

- heated length,
- cell type (unit cell, guide tube cell),
- hydraulic diameter and equivalent heated diameter,
- grid spacing,
- axial power shape, and others.

A justification or derivation based on measured CHF data is required for each of the geometry parameters mentioned above. Based on the analysis of GAIA CHF test data, the key parameters were identified. This process has allowed the GAIA CHF correlation using the ORFEO™ form to:

- avoid the dependence on a heated length parameter and
- improve the modeling at high qualities with a more consistent prediction of the impact of axial power shapes.

These actions will be individually discussed below.

A widely used parameter in PWR CHF correlations is the heated length, for example defined as length between the inlet and the axial location of DNB occurrence or as the total active length. The purpose of the heated length effect term is to adjust the CHF correlation result to the length of the fuel assembly.

AREVA has earlier analyzed the dependency of CHF on heated length for various spacer grid designs as well as for a wide range of test bundle geometries. Different heated lengths (8 ft. to 14 ft.) with uniform and non-uniform axial power shapes have been investigated. No significant dependency on the heated length was observed in this investigation. For this reason, AREVA is not using a heated length parameter in the ORFEO™ correlation form for GAIA. Preliminary analyses of the GAIA CHF tests also show there is no significant dependency on the heated length. The example in Figure 7 shows the absence of the heated length effect for CHF test data based on 12 ft. and 14 ft. test assemblies.

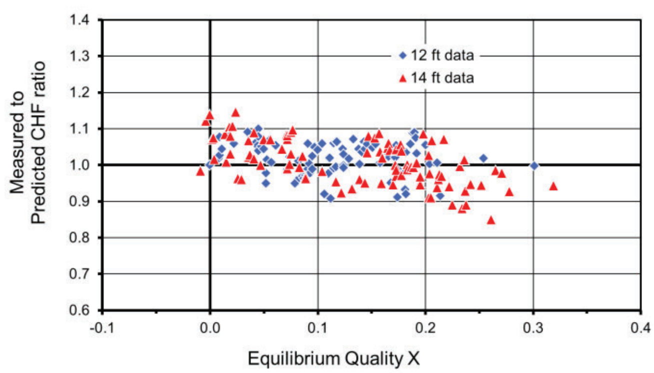


Figure 7. Comparison of 12 ft. and 14 ft. data

6. DEVELOPMENT OF THE ORFEO™ CORRELATION FORM

The ORFEO™ correlation form was developed by AREVA for generating CHF correlations for different fuel designs, not just for the GAIA fuel design. The robustness of the ORFEO™ correlation form is further reinforced by its establishment using the AREVA PWR database. The ORFEO™ correlation form:

- can be used to cover a large range of flow conditions as encountered in core studies, including low pressures (<1500 psia / <100 bar), low mass fluxes (<1 Mlbm/hr-ft² / <1350 kg/m²-s) and high qualities (>0.30),
- is applicable to the wide range of spacer grid designs via fuel assembly geometry parameters and spacer design specific coefficients, and
- provides a good (location) prediction of DNB occurrence for non-uniform axial heat flux shapes.

The basic form of the ORFEO™ correlation is as follows:

$$q''_{crit} = \frac{F_{BASE}(P,G,X,Z_{BO}) \cdot F_{Spacer}(P,G,X,gsp,dg,rtg)}{FNU}$$

P	: pressure
G	: mass flux
X	: equilibrium quality
Z_{BO}	: burnout length
gsp	: grid spacing
dg	: distance from upstream grid
rtg	: guide tube factor
FNU	: factor non-uniform

The F_{BASE} term reflects the general dependence of CHF performance on local thermal-hydraulic conditions and burnout length whereas the F_{Spacer} term reflects the further adjustment needed to represent the distinct dependence of CHF performance on a specific fuel design. The establishment of the F_{BASE} term is only possible due to the availability of the large AREVA PWR database of CHF measurements for various spacer grid designs. The dependence of the F_{BASE} on the AREVA PWR database and the F_{Spacer} term dependence on the fuel design specific testing are illustrated in Figure 8.

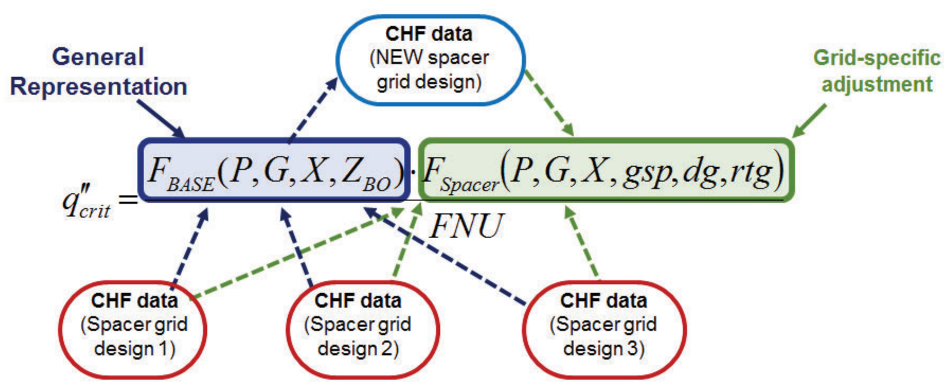


Figure 8. ORFEO™ CHF correlation form and its relation to CHF data on various spacer grid designs

The structure of the ORFEO™ correlation form has proven to describe the available databases for AREVA spacer grid designs effectively. Furthermore this approach allows an easy and early development of a CHF correlation for future fuel designs.

7. APPLICATION OF THE ORFEO™ CORRELATION FORM TO GAIA

The application of the ORFEO™ correlation form in developing a GAIA CHF correlation utilized the following criteria:

- good data coverage within the ranges
- good statistics on the development and validating databases
- good axial location prediction rates versus detection locations, and
- dependence on flow conditions and geometry parameters matches well with the experimental observations.

The correlating process included:

- the application of advanced fitting algorithms,
- finding the best correlation functional form (parameters)
- determining the empirical coefficients, and
- safeguarding against inaccurate predictions during interpolation, limited extrapolation, and behavior at the boundaries of the ranges

AREVA's correlation development process for a GAIA CHF correlation is still in progress, however, a preliminary GAIA correlation has been used to provide the measured-to-predicted (M/P) performance using the ORFEO^{TM} correlation form. The results are shown in Figure 9 for M/P versus quality, Figure 10 for M/P versus mass flux, and Figure 11 for M/P versus pressure. Furthermore the split into development and validation databases has been done along test campaigns. The data of four of the tested geometries has been set aside to validate the applicability of the correlation to geometry combinations not included in the development process. The database split is approximatively 60% for correlation development and 40% for correlation validation. Figure 9 to Figure 11 clearly demonstrate the capability of the ORFEO^{TM} correlation approach to cover a broad range of thermal-hydraulic conditions, but also to capture the variations in geometry.

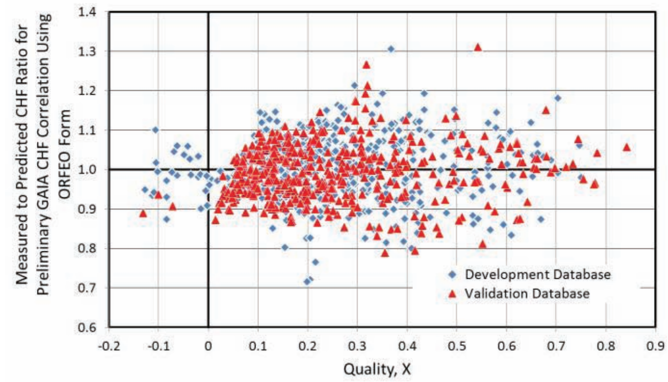


Figure 9. M/P versus quality with a preliminary GAIA CHF correlation using the ORFEO™ form

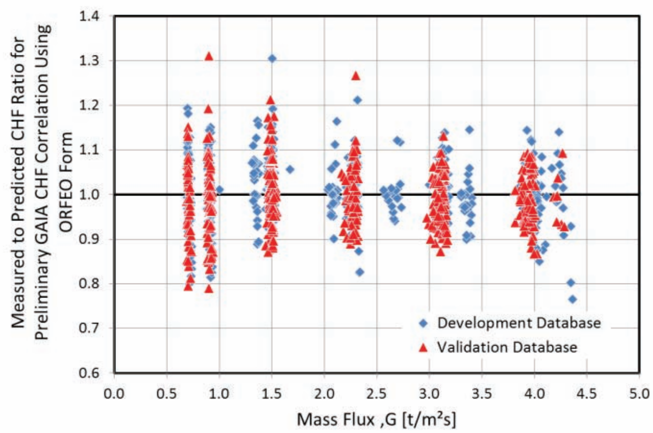


Figure 10. M/P versus mass flux with a preliminary GAIA CHF correlation using the ORFEO™ form

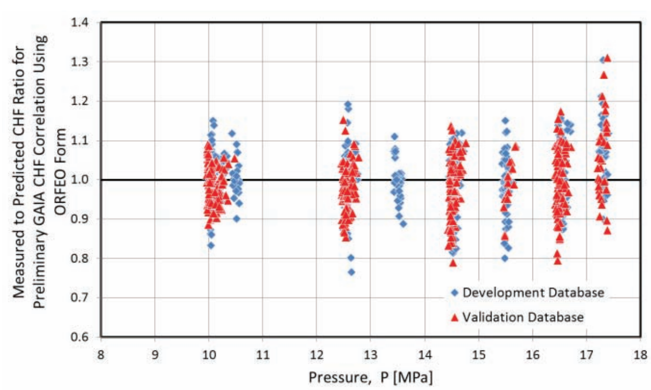


Figure 11. M/P versus pressure with a preliminary GAIA CHF correlation using the ORFEO™ form

The three figures show the good M/P distribution for the correlation development database as well as the validation database. Figure 9 shows the excellent performance of the burnout length parameter in the ORFEO™ form in reducing the M/P variability, particularly at the high qualities.

8. CONCLUSIONS

During the last decade, AREVA has compiled unique experience in correlation development that has led to an improved CHF correlation development process. This improved process is being effectively applied to produce a CHF correlation for the GAIA fuel assembly design using the ORFEO™ correlation form.

The ORFEO™ correlation form consists of a modular approach based on three terms: (i) a general representation term based on the CHF performance of multiple grid designs, (ii) a specific adjustment term that captures the CHF performance of a specific grid design and, (iii) a correction factor to account for the non-uniform axial power profiles. The ORFEO™ correlation form also accommodates two major contributions aiming at reducing the variability of the "Measured to Predicted CHF" ratio: (i) the introduction of the "burnout length" parameter and, (ii) the elimination of the "heated length" parameter.

The application of the ORFEO™ CHF correlation form to the GAIA CHF test database demonstrated the ability to accurately predict CHF test data that was not included in the correlation fitting database. The ORFEO™ correlation form accurately predicts CHF for a wide range of local thermal-hydraulic conditions as well as for the various geometries tested in order to describe the CHF performance of the GAIA fuel design.

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