Margins to Critical Heat Flux in Pressurized Water Reactors using Modern Thermal-Hydraulic Methods

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ABSTRACT

Critical Heat Flux (CHF) is one of the main safety parameter in design and operation of pressurized water reactors. However, there is neither physical modelling nor generally accepted correlation allowing directly applicable methodology and criterion for CHF analyses. On the contrary, a large number of factors play a significant role in the evaluation of CHF value and in the design of the means to protect the core of the nuclear reactor against CHF.

This paper will present all successive steps that are followed to support CHF related safety studies. Each step will be briefly presented associated with uncertainties, biases and possible sources of non-conservatisms.

As a detailed analysis of all these components is not possible in a single paper, main discussions will focus on the CHF correlation and the impact of the choice of possible databases and parameters would have on the determination of the margin to CHF in PWR reactors.

As a conclusion, it can be seen that the CHF analyses should be considered with a holistic approach where all components are deeply interrelated. Finally, the margins that are evaluated are highly dependent on the methods carried at each stage.

KEYWORDS
critical heat flux, departure from nucleate boiling, non-uniform axial flux shape, boiling crisis

1. INTRODUCTION

Critical heat flux (CHF) is designating the limiting value of heat flux when heat transfer dramatically drops due to boiling crisis or more specifically due to departure from nucleate boiling (DNB) in calefaction conditions. This corresponds to the formation of a vapor blanket surrounding and insulating the wall preventing efficient cooling by liquid. Margin to CHF is a key parameter in the thermal hydraulic design of not only a nuclear reactor but any boiler where water (fluid) is both cooling the elements providing heat but also carrying the energy outside.

A practical mean to determine the risk of boiling crisis is to form the so-called DNB ratio (DNBR) or CHF ratio (CHFR) of the predicted CHF to the actual (local, measured) CHF. The larger the ratio is above unity, the lower the risk of boiling crisis. But unlike other physical dimensionless number such as equilibrium quality for example where distance to saturation or full evaporation can be directly derived, there is no simple scale to link DNBR value to capacity to increase reactor power or even local heat flux. Comparing the obtained DNBR value to the unity has the advantage to be straightforward but is not giving any indication on the real advantage that can be withdrawn. Not only biases and uncertainties are not included, but it is very difficult to have a direct factor transforming a margin to power upgrade or to extended range of operation allowing higher values of axial offset, radial power distribution, or inlet conditions. However, the raw relative difference of the DNBR calculated in normal operation to DNBR criterion is very often the only indicated margin provided by the designer.

Some discussions about CHF margins occurred in 1996 ([1-3]) where pros and cons of ‘Direct Simulation Method’ (DSM) and ‘Heat Balance Method’ (HBM) exchanged their opinion, and in a similar vein, critical power ratio (CPR) and DNBR/CHFR methods, form of correlations were also discussed. The International Atomic Energy Agency (IAEA) issued a document presenting CHF prediction method for advanced water cooled reactors [4]. More recently a study [5] was proposed using look-up tables [6]. However, no real recommendation or clear common opinion is coming out although reliable evaluation of the margin to CHF is important information to the engineer because it is related to the thermal analysis of transients and accidents. Several reasons came to mind to explain the absence of consensus. First of all, this is a very sensitive subject where industrial property is highly involved. Improving DNB evaluation may allow direct benefit, either in rated power or in operation flexibility (core management, pressure-temperature range, …). Each designer has its own data and methods. Secondly, confusion arises when a common approach is adapted with both pressurized and boiling water reactors; parameter range, core design, core computer codes, accident analyses are very different between the two types of reactor. Even more, core thermal hydraulic design and loss of coolant analyses (LOCA) do differ dramatically both in nature and in objectives.

When it comes to CHF margin, this opens up a large variety of definition and interpretation. This paper will look the opposite direction. Are the established margins sufficient enough to ensure the safety of the installation? Do the actual margins cover the uncertainties and biases? Are they enough conservatism to cope with unexpected events? Main reason is that in comparison with first reactor designs, recent ones are putting forward lot of benefit coming from new fuel designs, new methods, new approaches of core protection that, added together, may significantly reduce the true margin to CHF. Therefore, core thermal hydraulic analyses should not consider only one aspect but have to carry out a ‘holistic’ analysis to check whether conservatisms or advantages brought to light somewhere would not lead to ‘negative feedback’ elsewhere. Unduly benefit might, in some specific conditions, arise from insufficient experimental support or analyses of the methods and applications.

This paper will present all successive steps that are followed to support CHF related safety studies. Each step will be briefly presented associated with uncertainties, biases and possible sources of design margins due to deficiencies in the methodology. As a detailed analysis of all these components is not possible in a single paper, main discussion will focus on the CHF correlation and the impact of the choice of possible databases and parameters would have on the determination of the margin. As the CHF correlation is the key factor in DNB studies, a practical application of the influence of correlation construction will be presented.

Only pressurized water reactors are considered and for evaluations and studies at high pressure and normal flows as low flow and/or low pressure involve additional considerations (limitation of computer codes, different physical phenomena).

2. DNB RELATED THERMAL-HYDRAULIC ANALYSES

As the fuel clad is the first barrier preventing release of radioactive material, boiling crisis is to be avoided at any time during normal operation of the reactor and in case of most frequent transients. DNB related core thermal hydraulic analyses rely on several components closely linked. CHF tests already existing or carried out for a specific fuel assembly serve to support the CHF correlation. A computer code is compulsory to perform the PWR core analyses to compute mass velocity and quality in the hottest part of the core. Then all transients for which DNB has to be avoided should be analyzed to define the corresponding set-points (alarm and trip) for the protection systems. Current modern methods take benefit of significant improvements that have been developed since the first design of PWR reactors.

2.1. CHF Tests

One key parameter in CHF related studies is to determine (and then benefit from) the CHF performance of the fuel. Research and development to design the grids have been carried out for decades and will probably continue to be a major concern of nuclear fuel industries. Although numerous attempts and significant progress in the last years have been made, there is no direct connection established between the grid components and the CHF performance. Therefore, the only means to determine CHF performance is to carry out CHF tests. This is also the only support that a regulatory body will accept for review and acceptance of core thermal hydraulic evaluations. But these high risk tests require significant funding for uncertain results. CHF performance might be disappointing or inconsistent.

Besides, open questions relative to the transposition of the test to the reactor are still open [7] as there are numerous causes of uncertainties, biases and deficiencies. In addition, test geometries to be tested and test matrices to be carried out are key elements for a trustworthy evaluation of CHF performance and for the elaboration of a reliable correlation. Our recommendation is, between geometries, to change one single parameter at a time, to cross check each change, and to focus on geometries representative to the core application (axial flux shape, full length, grid spacing) and to data conditions in the range of interest. Geometries that diverge from real fuel assembly geometry may offset (balance) negative effects occurring in geometries closer to real applications and therefore should not be the primary bases for reliable determination of CHF performance.

2.2. CHF Correlation and Computer Code

Once the data have been collected, the CHF performance evaluated in experiments should be transformed in practical tools to carry out core thermal hydraulic design analyses. For this reason, general CHF correlations or look-up tables [6] are of limited interest as they do not describe the actual performance of the product. However, if only a rough evaluation of achievable CHF in harsh conditions (LOCA) is needed, general correlations or tables provide sufficient estimation whereas precise correlations might be erroneous due to extreme thermal-hydraulic conditions or distorted geometries. In the next chapter, we will focus on some aspects of CHF correlations.

As core application based on CHF studies are relative to the smallest scale, the sub-channel, and in the hottest area of the whole reactor core, the correlation must use parameters that are not test dependent. For this reason, correlations using inlet temperature or enthalpy have to be considered with the utmost caution; in the experiments, inlet temperature is the chosen parameter (in addition to pressure and flow rate) as its control in the test loop is easy, but the parameter that is of interest in core applications is the quality. In reactor application, inlet temperature is set, and the great variability of local quality is due to the radial peaking factor (f_{xy}) and the axial flux shape.

Although quality is not mathematically independent of the heat flux, we should have enough confidence in the sub-channel computer codes to handle correct determination of quality as a local parameter. In addition, sub-channel computer code use is unavoidable in PWR CHF core analyses. This indeed introduces biases and uncertainties linked with the use of sub-channel codes. Main sources are the radial description (radial peaking, side of the test section) connected with the mixing capability of the grid (in particular the vanes) and the mixing coefficient that is an input in the code. We have to keep in mind that if the determination of the mixing coefficient was totally meaningful, CHF correlation would not need any adjustments. The CHF correlation is the key element to compensate the deficiencies and limitations of the sub-channel computer codes.

2.3. CHF Criterion

Another difficulty is to establish the DNBR criterion; the level DNBR has to be above unity in order that only marginal risk to get boiling crisis remains. A standard admitted procedure is to ensure that there is a 95% confidence that 95% of the population of (experimental or measured) CHF have a value equal or higher than the predicted CHF. For historical reasons, the usual practice is to form the measured to predicted ratio (M/P). The difficulty that arises is to evaluate the 95% of the population based on samples (the test data) and, connected to that, the 95% confidence. It is accepted to use the OWEN one-sided tolerance limit [8]. But this approach requires a normal distribution. In addition, no trends with parameters and homoscedasticity (same variance for all parameters over the full range) are essential. When test to check the normal distribution fails, it is sometimes proposed to use of non-parametric tolerance limits (Wilks, Murphy, Sommerville, …). There are several issues related to the way to circumvent this problem. First if non-parametric methods might be acceptable in relation to Monte Carlo procedures, for CHF experiments, test matrix is all but a random process. Secondly, the different CHF correlations provided in next chapter clearly show that changing the correlation parameters have a significant impact on the distribution of the M/P values, thus these M/P values are absolutely not random variables. Lastly, a non-normal distribution can be an indication of a defect in the procedure (some erroneous data, a test series that is not compatible with others, an incorrect choice of parameter, …).

Homoscedasticity is naturally closely related to the reliability of the upper tolerance limit. When higher scatter (variance) is observed, development of two separate correlations for the two different zones (with some overlapping) is preferable to the computation of two values of tolerance limit, one for the 'normal' scatter, the other for parameter range having a higher scatter. The second option might be much more favorable in terms of resulting tolerance limit value, as the sample size is larger but the impact on the correlation should be carefully studied as the values of the coefficients might be significantly impacted. Therefore, although the implementation of several correlations in the computer code or the protection system introduce additional constraints, this option might be preferable as dedicated tools for specific analyses and studies are better than a general tool.

2.4. Transient Analyses

Safety considerations (and nuclear regulations) impose, in thermal hydraulic transient and accident analyses, to avoid DNB in case of any 'frequent' event occurrence (anticipated operational occurrences) [9] which means that the DNBR should be sufficiently high to avoid DNB if such an event occur. As during this event, DNBR value may dramatically fall (during the first seconds of the transient when power is still high), under normal conditions the DNBR value must be sufficiently high to cope with such a drop. This implies that the local thermal-hydraulic conditions are such that CHF is very high with an order of magnitude of 50 to 100% above the local heat flux (DNBR value between 1.50 and 2.00). Therefore experimental conditions to measure critical heat flux under such conditions might not be reasonably achievable. Most of the times, it is necessary to extrapolate (either with pressure, mass velocity or quality) in order to compute the predicted CHF.

As under normal operation local heat fluxes must be quite away from critical heat flux, to our knowledge occurrence of DNB was never experienced in nuclear reactor. The latter makes it very tempting to operators and designers to reduce possible over-conservatisms and take benefit from this. This is why statistical core designs have been developed [10-11] providing significant gain based on method only and no 'physical' change in the reactor (such as fuel assembly with better performance).

One question remains to identify what is margin and what conservatisms should be considered to take into account all biases and uncertainties. Conservatisms cannot be considered as margin and margins sometimes are quite useful to cover phenomena, biases and uncertainties that were not forecast or estimate at the design phase.

2.5. Protection System

As DNB must be prevented during operation and in case of anticipated operational occurrences, automatic system is designed to protect the core against it. Historically first type of system (analogue) determine authorized domain of operation and limiting set-points. As DNB is not a directly measurable value, it is controlled by monitoring the vessel outlet to inlet temperature difference and average, and system pressure [12]. New digital technology that allow fast calculations permit to design protection system that compute directly the DNBR [13] with a constant comparison with DNBR limiting set-points. This is indeed a more efficient way and is intended to allow more flexibility in the operation of the reactor by removing envelop parameters that needed to be included when computing the over temperature ΔT trip set-points of the analogue systems. The upper-bounds limits related to the construction of over delta-temperature are no longer present in on-line processing of DNBR.

3. HEATED LENGTH AND AXIAL FLUX SHAPE IN CHF CORRELATIONS

The CHF correlation is the common denominator in all steps described in the previous chapter. The correlation is the means to describe the CHF performance of the fuel assembly evaluated in the tests. The correlation is essential in transient analyses and the correlation is the central element for the core protection system. For this reason, we propose to take a closer look at the variability of the CHF depending on the options chosen to build the correlation.

In order to present some quantitative values, our discussions will be based on experimental data that are publicly available. Using the same data points, several options will be selected to compare the corresponding CHF values obtained. The options will be on the selected test series and on the parameters included in the regressions.

3.1. CHF Test Series

In order to avoid too many parameters to be tested in the regressions, tests will have very close configurations with the same grids, the same grid spacing (559 mm), the same number (25) of heating rods (no guide tube or cold rod), same test section side (65.1 mm) and similar radial peaking (central to peripheral around 1.20). Three test series are considered with two heated lengths[1]; 2.44 m (8 feet) and 4.27 m (14 feet) and two axial flux shapes (uniform and cosine). These test sections, number E160, E161 and E164 from the Westinghouse Electric data, are extracted from [14], a valuable compilation of 235 test sections assemblies with a total of 11077 CHF data points. Only data points having a common range of pressure (10-17 MPa) and mass velocity (1300-4500 kg/m²-s) are considered, making about 70 conditions per test series.

3.2. Non Uniform F-factor

The dependency of CHF values with the axial flux shape of the heated rods have been identified for a long time. Several approaches have been proposed, such as a bubble-layer thermal shielding [15]. With simpler terms, the cause of this dependency might be interpreted as different distribution of the quality (and void fraction) within the sub-channel. A multiplicative correction factor, referred to as the F-factor, is usually accepted with various values for the coefficients proposed. Although it is a key element for a proper evaluation of the occurrence of boiling crisis, there is no totally satisfying proposal. It is important to have in mind that this correction is the only means to handle core applications due to the infinite variations the

[1] In the text, test series heated length will be given in foot as they are round numbers. All other units are SI.

axial flux shape may be subjected to. A detailed analysis is not possible in this paper and some deficiencies, some difficulties, some challenges have been identified in [16]. A detailed study is out of the scope of this paper and we will adopt the Tong's model and its coefficients proposed in [15] with a minor correction described later (chapter 3.3.1 – equation 1).

3.3. Results

With only three test configurations, considering only the local values of pressure, mass velocity and quality, testing also the heated length and using one set of coefficients for the F-factor, the amount of results is already quite difficult to analyze. We will present our work in two fold; first with a limited set of parameters considered in the regressions (Pressure P, mass velocity G and quality X, cross products and squares of pressure and mass velocity), and then considering a larger set of parameters adding heated length, with associated cross products, and quality at the power of two. Only linear regressions are considered with the optimization of the coefficients based on the least square method with significant parameters selected mostly by a test and try approach.

It might be questionable to compare different correlations which are based on different sets of data. In fact this is the key question during the construction of the correlation related to its capacity to 'predict' reliable values of CHF when applied to other geometries that were not available (or considered) during the construction phase. This can be a good indicator of the reliability and the robustness of the correlation, much more interesting than splitting the database in two part, one for construction and the other for verification.

3.3.1. Reduced set of parameters

To begin with, it was natural to consider the closest test configuration to the actual fuel assembly in the core, the 14ft geometry. The data points from the E161 test series were used to optimize a CHF correlation resulting in quite satisfying statistics. Indeed, this is the least we could expect considering only one geometry and 71 data points. With the constant and five parameters (P, P^2, G^2, PX and GX; G, X and PG did not improve the quality of the correlation) the statistics computed with the measured to predicted ratios (M/P) showed good accuracy with data points but poor results with other test series as summarized in the following Table:

Table I. Reduced Set of Parameter optimization of coefficients with E161 Data

Regression RR-U14-F0 based on E161 (14 ft uniform) data

$$CHF_{RR-U14-F0} = 4.268358-0.33254585*P+0.01070461*P^2+0.033815424*G^2-0.1376517313*PX-1.014880*GX$$

Test #	Mean	Std. dev.	Data	Min M/P	Max M/P
E161	1.000	0.042	71	0.904	1.079
E160 (8 ft uniform)	1.162	0.108	67	0.911	1.367
E164 (14 ft cosine) No F-factor	0.872	0.105	76	0.691	1.112
E164 with F-factor	1.100	0.099	76	0.911	1.416
E164 with F-factor corrected by constant factor 0.590	1.007	0.093	76	0.822	1.246

It can be concluded that on one hand the lower heated length data points (E160) do reach significantly higher CHF values than the ones with 14ft heated length. On the other hand, CHF is lower when measured in the non-uniform test series[2]. The F-factor is too large and the resulting predicted value of CHF is, in average, 10% lower than the measured CHF. The process to determine new sets of coefficients for the F-factor being long and tedious, a shortcut was considered in this study and a constant overall corrective factor is introduced. Indeed this is not the preferred option to finalize a correlation used for safety studies but this a sufficient tool to carry out the present study. A corrected F-factor value (F_{corr}) was calculated from the original F-factor value (F_{or}), as calculated in [15], with a constant factor K following the relationship:

$$F_{corr}=1. + (F_{or}-1.)*K \quad (1)$$

To adapt the 14 ft cosine test to the 14 ft uniform test, the constant K=K1 is equal to 0.590.

The second phase is to include the cosine data points[3], either with the F-factor values as calculated initially or the F-factor values corrected with a constant value as in equation (1) and then re-optimize the coefficients. The results are summarized in Table II and III respectively.

Table II. Reduced Set of Parameter optimization of coefficients with 14 ft uniform and cosine data and original F-factor

Regression RR-UC14-F1 (Tong F-factor) based on E161 and E164 data $CHF_{RR-UC14-F1} = 6.7851-0.61455*P-4.5951*X+0.016911*P^2+0.0152843*PG +0.22616905*PX-1.2768422*GX$					
Test #	**Mean**	**Std. dev.**	**Data**	**Min M/P**	**Max M/P**
E161-E164	1.001	0.081	147	0.845	1.289
E160 (8 ft uniform)	1.102	0.101	67	0.836	1.279
E161 (14 ft uniform)	0.959	0.056	71	0.845	1.138
E164 with F-factor	1.039	0.082	76	0.862	1.289

The standard deviation calculated with the data used for the optimization has doubled, the discrepancy of the F-factor has been ‘shared’ between the uniform and the cosine test series. If this behavior appears clearly it is because we considered only two test series with a similar number of data points and parameter range.

We tested the second option to consider an F-factor which is more representative using the correction proposed in equation (1), with a constant factor K1=0.590.

Table III. Reduced Set of Parameter optimization of coefficients with 14 ft uniform and cosine data and corrected F-factor

Regression RR-UC14-F1m (Tong factor corrected with constant factor K1=0.590) $CHF_{RR-UC14-F1m} = 5.787102-0.503301*P-2.679468053*X +0.015651513*P^2+0.0225093*G^2-0.758664*GX$					
Test #	**Mean**	**Std. dev.**	**Data**	**Min M/P**	**Max M/P**
E161-E164	1.001	0.067	147	0.824	1.255
E160 (8 ft uniform)	1.154	0.116	67	0.877	1.384
E161 (14 ft uniform)	1.002	0.054	71	0.905	1.154
E164 with corrected F-factor (0.590)	1.000	0.078	76	0.824	1.255

[2] M/P higher than1.00 for cosine axial flux shape occur at the lower pressures.

[3] Local conditions are considered at the axial location where DNB where recorded (either upstream from the penultimate or the third last vane grids)

We obtain quite acceptable results. Indeed, most of the 8ft uniform data have a quite larger measured critical heat flux than the ones calculated by the correlation but, as the 8 ft heated length is not representative of the real fuel assembly, it might be acceptable to discard this test. In addition, it is clearly shown that there is a beneficial effect, therefore we do not risk any non-conservatism if we do not consider this test. The correlation has a limited number of six coefficients. Figure 1(a) shows the scatter plots of the M/P with quality. The 8ft data are distributed for lower qualities and it seems that a large part of these data cannot mix with the other ones.

Under uniform heating conditions, most the CHF prediction is within +/-10% with a limited number of M/P out of the 0.90-1.10 range. Although most of the cosine data stays within this range, the scatter appears clearly higher than for the uniform test. A slight trend with mass velocity can also be noticed in Figure 1(b).

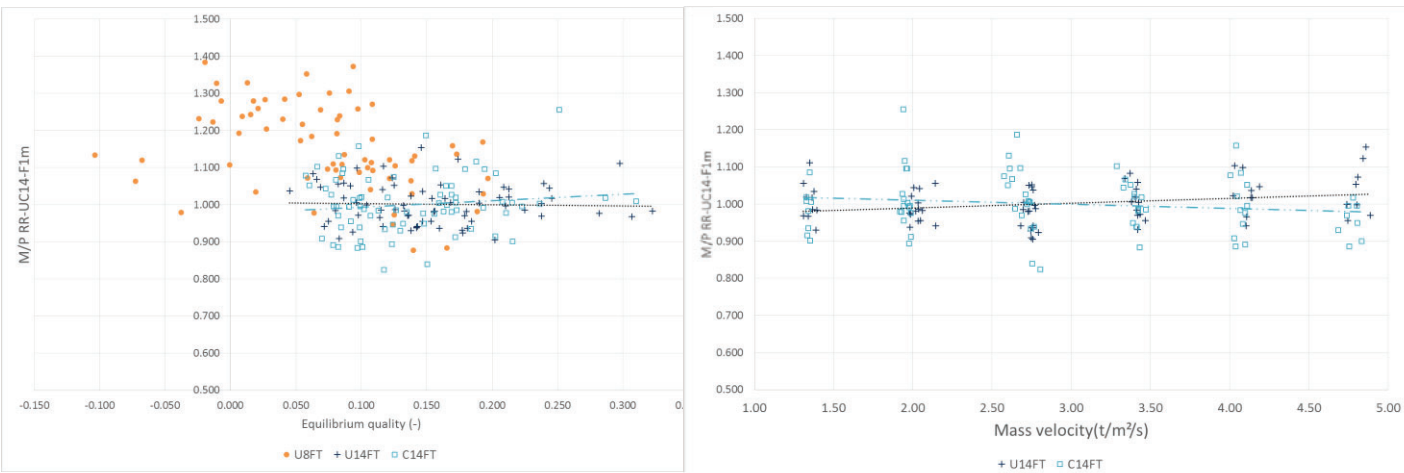

Figure 1. Scatter plots of M/P (a) all test series with quality (b) 14ft test series with mass velocity

It is also of interest to see how the correlations behaves with local conditions as we do not have exactly the same parameters used. The mathematical variation of CHF with quality at a given pressure (15.5 and 12 MPa) and mass velocity (3500 and 2000 kg/m²-s) compares the slopes of CHF with quality (Figure 2).

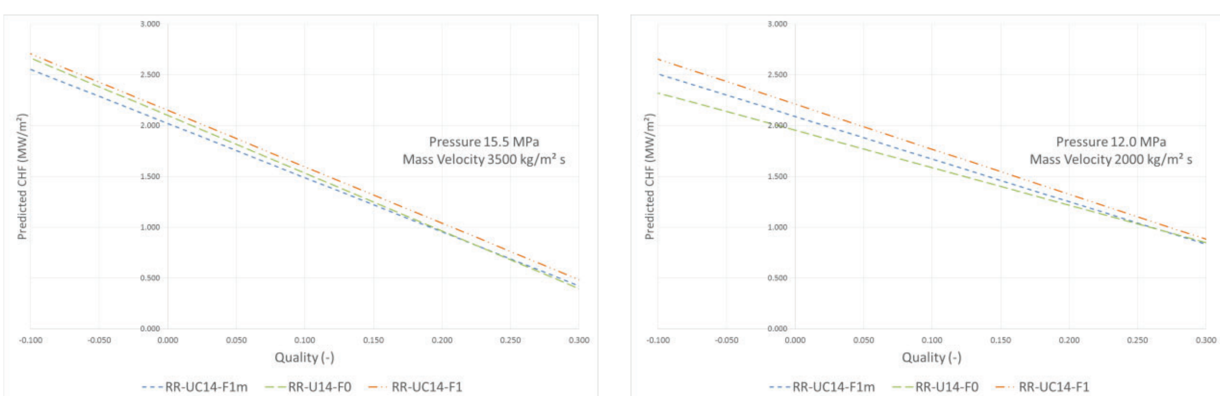

Figure 2. Comparison of regressions using reduced set of parameters

The correlation using the F-factor 'as it is' (RR-UC14-F1) is clearly above the other curves at the chosen values of pressure and mass velocity. Variations with pressure and mass velocities show similar trends but are not plotted to limit the number of pages of this paper. However, a real comparison should be made in non-uniform axial flux shape applications to see how each value of F-factor modify the uniform correlations.

3.3.2. Full set of parameters

Let us see now how the addition of new parameters would transform the behavior of a CHF correlation. The heated length L with cross products PL, GL, XL and the X|X| product were introduced in the regressions. As a first step, only uniform data (8 and 14 ft) are used to optimize the coefficients. Table IV summarizes the statistics computed with the measured to predicted ratios (M/P) which showed good accuracy with data points but discrepancy with the cosine test with or without F-factor. It was also found that the addition of the X|X| did not improve the accuracy of the regression.

Table IV. Full Set of Parameters optimization of coefficients with uniform data

Regression FS-U-F0 based on E160 & E161 (8 and 14 ft uniform) data

$$CHF_{FS-U-F0} = 7.251 - 0.50226*P - 0.413954*G - 11.3139*X + 0.0121222*P^2 + 0.039045034*G^2 + 0.0281555417*PG + 0.4438018*PX - 1.2296361*GX - 0.0138994587*PL + 0.82660414*XL$$

Test #	Mean	Std. dev.	Data	Min M/P	Max M/P
E160 & E161	1.000	0.064	138	0.813	1.283
E160 (8 ft uniform)	0.999	0.066	67	0.813	1.131
E161 (14 ft uniform)	1.001	0.062	71	0.902	1.283
E164 (14 ft cosine) No F-factor	0.826	0.093	76	0.633	1.053
E164 with F-factor	1.044	0.105	76	0.853	1.377
E164 with F-factor corrected (0.795)	1.000	0.097	76	0.808	1.295

The heated length parameter improves significantly the prediction of the 8ft uniform data but results in the deterioration of the 14ft uniform data prediction. The F-factor is again too large, and the resulting predicted value of CHF is in average about 4.5% lower than the measured CHF. The F-factor was adapted with a constant factor K following the relationship (1), the value of the constant K2 is 0.795.

The second phase is to include the cosine data points and re-optimize the coefficients, either with the F-factor values as calculated in the original form or adapted with a constant value using equation (1). The results are summarized in Table V and VI respectively. Note that with the original F-factor, the X|X| parameter has been detected as a good correlation parameter, but not for the corrected F-factor.

Table V. Full Set of Parameters optimization of coefficients with all three test series and original F-Factor

Regression FS-A-F1 (Tong factor) based on E160, E161 and E164 data

$$CHF_{FS-A-F1} = 6.304921 + 8.74774029*X|X| - 0.46855018*P - 9.99809*X + 0.012027505467*P^2 + 0.0155395226*PG + 0.42617*PX - 1.217*GX - 0.0087308843*PL$$

Test #	Mean	Std. dev.	Data	Min M/P	Max M/P
E160-E161-E164	1.000	0.074	214	0.767	1.246
E160 (8 ft uniform)	0.994	0.075	67	0.767	1.134
E161 (14 ft uniform)	0.988	0.062	71	0.870	1.233
E164 with F-factor	1.017	0.081	76	0.841	1.246

The discrepancy of the F-factor has been reduced and the average M/P for each test series individually is within +/-2% around unity. The next phase is to consider an F-factor which is more representative using the correction proposed in equation (1), with a constant factor K2=0.795.

Table VI. Full Set of Parameter optimization of coefficients with all uniform and cosine data and corrected F-factor

Regression FS-A-F2m (Tong factor corrected with constant factor K2=0.795) $CHF_{FS\text{-}A\text{-}F1m} = 6.603615-0.4647597*P - 8.8109057*X + 0.0115353*P^2 + 0.01583457*PG + 0.253892355*PX - 1.31307*GX - 0.254077*L + 1.138886378*XL$					
Test #	**Mean**	**Std. dev.**	**Data**	**Min M/P**	**Max M/P**
E-160-E161-E164	1.000	0.073	214	0.797	1.229
E160 (8 ft uniform)	1.002	0.074	67	0.797	1.152
E161 (14 ft uniform)	1.001	0.065	71	0.876	1.229
E164 with corrected F-factor (0.795)	0.998	0.079	76	0.812	1.200

We obtain quite acceptable results. The scatter plots (Fig. 3) shows the opposite trend in mass velocity for 14ft test series uniform and cosine and surprisingly a data point from the uniform 14ft test at 4000 kg/m²-s (and quality around 0.21) with a M/P higher than 1.20 (same point with RR-UC14-F1m correlation has a M/P value of 1.047).

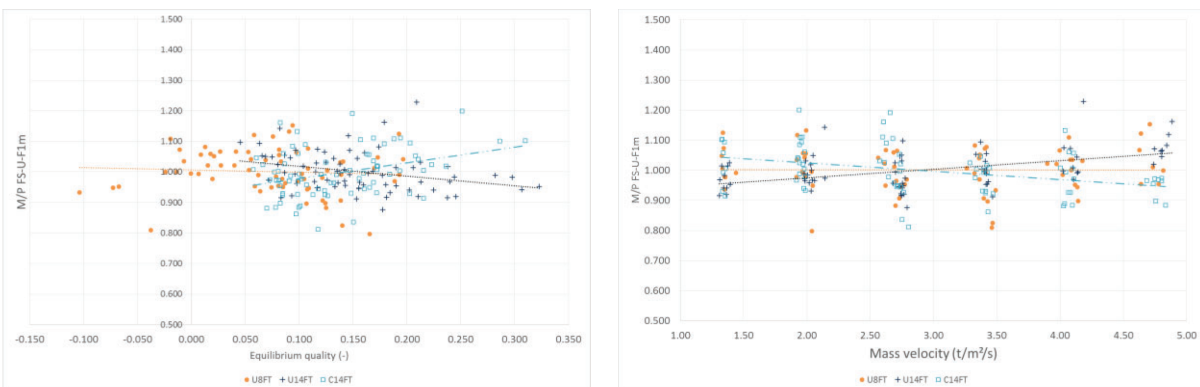

Figure 3. Scatter plots of M/P for all test series (a) with quality (b) with mass velocity

We plotted the mathematical variation of CHF with quality at a given pressure (15.5 & 12 MPa) and mass velocity (3500 & 2000 kg/m²-s), the slope is more important for the correlation based on uniform tests only (FS-U-F0; Figure 4).

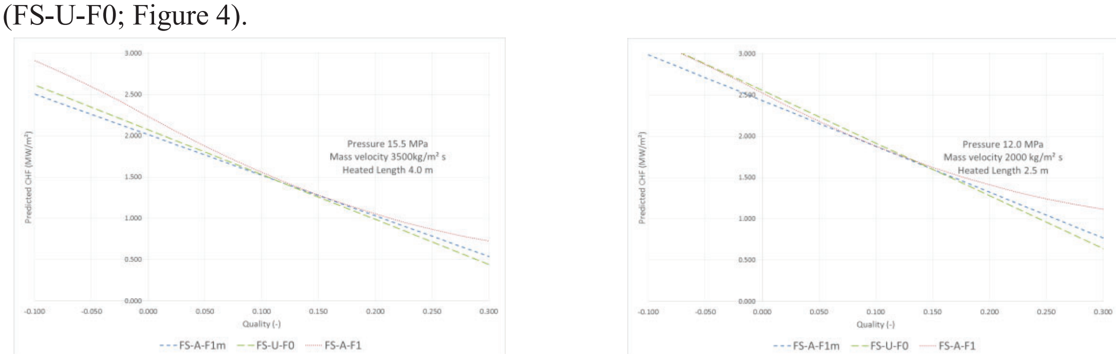

Figure 4. Comparison of regressions using full set of parameters

The term X|X| in the FS-A-F1 correlation using the F-factor 'as it is' clearly changes the behavior of the curve at the limits of the range covered by the experimental data. Dependence with pressure and mass velocities are not plotted as they do not show any additional trend compared to the differences between each correlations plotted with quality.

3.4. Synthesis

Core applications have been simulated using all correlations with their corresponding F-factor. Two values of pressure (15.5 and 12 MPa), two values of mass velocities (3500 and 2000 kg/m² s), two values of qualities (0.05 and 0.25) and two values of elevation (3.404 and 2.845 m) are considered; F-factor as given at these elevations and for the corresponding local conditions are considered, for the RR-U14-F0, RR-U14-F1, FS-U-F0 and FS-U-F1 correlations, the original F-factor is applied. Assuming a cosine axial flux shape, the predicted CHF values are compared in Tables VII and VIII. There are significant differences between each correlation but there is no systematic order. Interesting to note is that the FS-U-F0 correlation which should be conservative (optimized with uniform data and with an uncorrected F-factor leading to an average M/P value of 1.044) shows the highest CHF predicted value at 12.5 MPa and X=0.05. The FS-A-F1 correlation shows large beneficial difference at high qualities (0.25) for the 15.5 MPa conditions.

Table VII. Comparison of predicted values of CHF at 15.5 MPa for six correlations

Case / Correlation	AAA1	AAA2	AAB1	AAB2	ABA1	ABA2	ABB1	ABB2
RR-UC14-F1m (MW/m²) ⌘	1.515	1.652	0.543	0.642	1.438	1.540	0.635	0.732
RR-U14-F0 (MW/m²) ❖	1.431	1.642	0.467	0.604	1.319	1.472	0.555	0.691
RR-UC14-F1 (MW/m²) ❖	1.477	1.694	0.525	0.678	1.320	1.473	0.630	0.785
FS-A-F2m (MW/m²)❁	1.554	1.841	0.564	0.683	1.373	1.604	0.674	0.793
FS-U-F0 (MW/m²) ❖	1.502	1.811	0.496	0.646	1.343	1.588	0.588	0.736
FS-A-F1 (MW/m²) ❖	1.540	1.835	0.653	0.911	1.377	1.606	0.742	0.992
Relative overall difference	8%	11%	34%	44%	9%	9%	29%	38%
Mass velocity (kg/m²-s)	3500	3500	3500	3500	2000	2000	2000	2000
Local quality (-)	0.05	0.05	0.25	0.25	0.05	0.05	0.25	0.25
Elevation (m)	3.404	2.845	3.404	2.845	3.404	2.845	3.404	2.845
Tong F-factor (-) ❖	1.269	1.106	1.452	1.123	1.223	1.096	1.406	1.128
Corrected F-factor (-) with K1 ⌘	1.159	1.063	1.267	1.073	1.131	1.056	1.239	1.076
Corrected F-factor (-) with K2 ❁	1.214	1.084	1.359	1.098	1.177	1.076	1.323	1.102

Table VIII. Comparison of predicted values of CHF at 12 MPa for six correlations

Case / Correlation	AAA1	AAA2	AAB1	AAB2	ABA1	ABA2	ABB1	ABB2
RR-UC14-F1m (MW/m²) ⌘	1.735	1.892	0.745	0.879	1.663	1.781	0.841	0.969
RR-U14-F0 (MW/m²) ❖	1.555	1.784	0.642	0.830	1.448	1.616	0.736	0.917
RR-UC14-F1 (MW/m²) ❖	1.710	1.962	0.620	0.801	1.628	1.817	0.785	0.978
FS-A-F2m (MW/m²)❁	1.783	2.097	0.638	0.774	1.680	1.940	0.812	0.959
FS-U-F0 (MW/m²) ❖	1.765	2.088	0.513	0.643	1.737	2.003	0.709	0.864
FS-A-F1 (MW/m²) ❖	1.793	2.110	0.669	0.917	1.707	1.958	0.816	1.069
Relative difference	14%	16%	36%	34%	18%	21%	17%	21%
Tong F-factor (-) ❖	1.269	1.106	1.452	1.123	1.223	1.096	1.406	1.128
Corrected F-factor (-) with K1 ⌘	1.159	1.063	1.267	1.073	1.131	1.056	1.239	1.076
Corrected F-factor (-) with K2 ❁	1.214	1.084	1.359	1.098	1.177	1.076	1.323	1.102

Finally, trends of the correlations have been compared to the ones presented in [17], the same thermal hydraulic values being chosen (P=15 MPa, G=3 t/m²-s, X=0.15). As heated length is a parameter in the FS correlations, we adopted L=4 m for comparison, as this is the value which correspond to the 14 test used in RR correlations. As a matter of fact, CHF in [17] are about 0.5 MW/m² higher and only the trend with quality could be pasted. Thus we had either to distort the scales or to have only partial comparison. The former was preferred; the comparison is easier with identical scales.

- With pressure (Fig. 6a), we have similar behavior with same order of magnitude in the fall of CHF, about 0.6 MW/m² between 10 and 17 MPa in our case and 0.4 MW/m² in [17],
- With mass velocity (Fig. 6b), the trend is close to linearity in [17] with an increasing CHF of around 0.30 MW/m² between 1 and 4 t/m²-s. Fig. 6b does not present the same trend, with a smaller variation of about 0.1 MW/m²-s on the same range, and some correlations have a minimum CHF at 2.5 t/m²-s.
- With quality, trend and slope are similar (Fig. 6c).

It has to be reminded that the test series are different between this study and [17], this can explain part of the absolute difference in the CHF values. It is however surprising that CHF behaviors with pressure and with quality are so similar whereas for mass velocities a significant difference is observed.

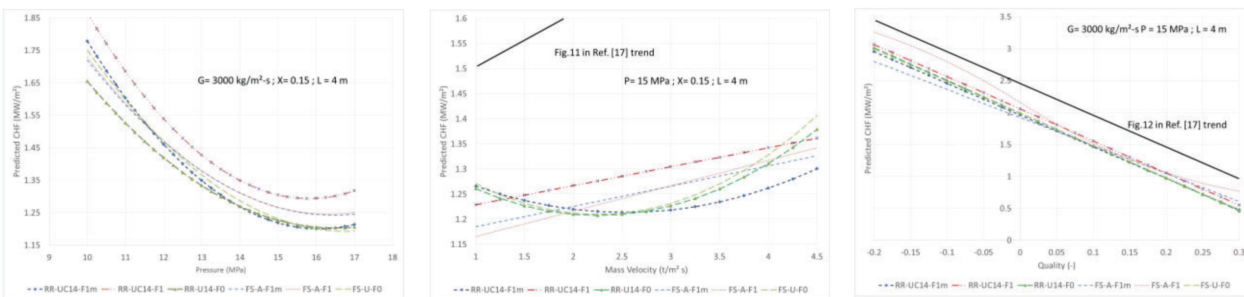

Figure 6. Comparison of calculated CHF with (a) Pressure, (b) Mass Velocity and (c) Quality

4. CHOICE OF PARAMETERS IN THE CHF CORRELATION

The previous study was limited to

- the parameters taken into account; the basic thermal-hydraulic quantities pressure, mass velocity and quality, with and without heated length and/or squared quality,
- the geometries compared, where only the heated length and/or the axial flux shape changed.

Even on this limited case study, significant differences were found in predictions of critical heat flux. With the elements in our hands, it is difficult to assess which correlation is or is not biased. Neither are we able to determine precisely the uncertainty to be applied in core applications. In fact multiple correlations can work, but should, at the end, lead to close predicted values of CHF. For this reason, great caution should be taken when considering the inclusion of high order parameters and/or non-local parameters and/or geometry parameters. Very large databases mixing all types of tests more or less related to real applications, and very large validity range may also raise concerns about the accuracy of the correlation.

Another indication given by our study is that conservatisms shown by statistics (average M/P higher than unity for example) do not necessarily provide lower predicted values of CHF (thus lower DNBR) when applied to some core conditions.

Some additional remarks on other parameters generally encountered in CHF correlation for PWR, and possible sources of biases and uncertainties, are presented hereafter.

To allow comprehensive core DNB analyses, the impact of a guide-tube (thimble cell configuration) is compulsory. When the grid spacing is not kept constant along the core length, this parameter might also be investigated. In addition, the distance to the grid spacing is sometimes introduced, mostly, to our point of view, for cosmetic purposes but not without possible biases. At last but not least, fuel assembly geometries are also sometimes mixed. In some databases, can be included test data with several rod diameters, pitch between rods, guide tube diameters, and even grid designs. Sometimes, geometry differences are modelled through the use of the equivalent hydraulic (or heated) diameter, which indeed is not a proper term, therefore no interpolation or extrapolation between each test values should be authorized. If the industrial interest is understood, as this permits to simplify the generation of the of a single CHF correlation and to allow its licensing for all type of cores, the accuracy of the correlation is more questionable.

A detailed analysis cannot be provided in this article as it goes beyond the means and time allowable. However, a clear good option is to try to separate all effects and carry out the analyses step by step on a single separate effect. Compensation effects, most of the time changing with local thermal-hydraulic parameters, might introduce erroneous models. Therefore, trying to correlate data coming from tests with multiple changed parameters (simultaneously heated length, grid spacing, rod diameter, …) leaves a lot of open issues.

Besides the question of the selection of the relevant parameters, the approach for non-uniform axial flux shape is essential. The study in Chapter three showed that the value of the F-factor is closely related to the correlation. Original set of coefficients did not fit correlations neither the one using the reduced set of coefficients nor the one using the full set. Corrections to be applied were also very different. But the key element is to find the association of the correlation parameters and F-factor allowing a good prediction of the location of boiling crisis. For core applications, indeed the location of boiling crisis is not known and have to be predicted. Therefore, the minimum value of DNBR is selected and provide the minimum gap between the predicted CHF value and the local value of heat flux.

The logical approach is to consider, during the construction and assessment of the correlation, the minimum predicted to measured ratio (thus the maximum M/P value). But in that case, at the elevation where the boiling crisis occurs, the local value of M/P is equal or lower than the maximum value. With coefficients of correlation optimized to have the maximum M/P value at unity, except for a perfect match of experimental location of boiling crisis and elevation where M/P is maximum, we will have for some data points an M/P lower than unity and thus a measured CHF lower than the predicted CHF, which indeed is not acceptable. Having 'somewhere else' DNB and not being able to anticipate DNB where it actually appears raise the problem of application of the correlation to any axial flux shape variation. The shapes used in the tests have a very low probability to be the ones in the core. In addition, in transient analyses, there is no reliable means to select the envelope of the axial flux shape. As the F-factor is closely related to the type of correlation (and more specifically if the correlation includes the heated length as a parameter), a high level of good prediction is essential. However, the overall percentage is not sufficient. The prediction capacity of the correlation should be evaluated at each measured location. In addition, the difference between the maximum M/P and the value at DNB location is to be evaluated for each data point and not globally.

5. CONCLUSIONS

DNB analyses are the basis of the core thermal-hydraulic design of a pressurized water reactor. As DNB is to be avoided for all anticipated operational occurrences, sufficient margin to DNB should be provided during normal operation. The core thermal-hydraulic design relies on several supports from experiments to core protection systems but the central tool is the CHF correlation. CHF correlations are very sensitive not only to the experimental support but also to the modeling.

Core thermal hydraulic design of recent reactors take benefit of large improvements both in fuel assembly designs, statistical methods, transient analyses, and the use of digital protection systems. This results in a possible reduction of the real operational margins to DNB. A lot of issues are still open and some methodologies have not been actualized since the 70s. A lot of sources of biases or uncertainties have been identified in this paper. There are, by construction, contained in the CHF correlation, some coming from deficiencies in experimental support, other from codes and methods. All propagate in transient analyses and determination of set-points of the protection system. A global (holistic) approach is therefore essential to assess the reliability of the modern core thermal-hydraulic studies. Finally, the margins that are evaluated are highly dependent on the methods carried out at each stage.

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