

QUANTIFICATION OF INPUT UNCERTAINTIES BASED ON VEERA REFLOODING EXPERIMENTS

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ABSTRACT

Propagation of input uncertainties through code runs and statistical analysis of the results has come to be one of the two prevailing methods when performing Best-Estimate Plus Uncertainty (BEPU) analyses with thermal-hydraulic system codes. To use the method, the uncertainties of the inputs need to be defined. A difficult task in this respect is the quantification of the uncertainties of the constitutive equations of the code. For this reason several methods to estimate the uncertainties of reflooding related correlations have been under review in the OECD/NEA-endorsed PREMIUM benchmark, in which VTT has also been taking part.

In this paper the same methodologies that were utilized by VTT in PREMIUM for quantification of the uncertainties, the FFTBM and CIRCE methods, have been used with data from the VEERA reflooding experiments. The experiments were performed in the 1990's at the Lappeenranta University of Technology VEERA facility in Lappeenranta, Finland in partnership with VTT.

The code used to perform the analyses was the APROS thermal-hydraulic system code, which has been developed by VTT in partnership with Fortum Ltd since 1986. The quantification results obtained with the VEERA data were furthermore compared to the VTT results obtained with the FEBA facility reflooding data during the PREMIUM benchmark.

Some issues with the VEERA data were identified during the analysis, due to which a part of the data was excluded. Even then it was possible to successfully perform a process of quantification of the uncertainties with the methodologies involved. The comparisons with the PREMIUM results revealed that even with the issues with the data intriguing results could be reached.

KEYWORDS

BEPU, Input Uncertainty, Physical Models, FFTBM, CIRCE

1. INTRODUCTION

The research of using Best-Estimate Plus Uncertainty (BEPU) methodologies in conjunction with APROS thermal-hydraulic system code has been an area of interest at VTT for some years now. It has risen from the global tendency towards taking uncertainties into account to provide more comprehensive safety analyses of nuclear installations [1-3].

At VTT the research has focused on a statistical method to evaluate the uncertainties related to simulation results by propagation of input uncertainty through the code runs. This method is often referred to as the

GRS method after the German research organization Gesellschaft für Anlagen- und Reaktorsicherheit, which pioneered its use in nuclear thermal hydraulics [4].

To provide reliable results the statistical method requires the uncertainties of the inputs to be well defined. In the case of physical parameters, such as inlet water velocity, the uncertainty can be related directly to the measurement error. With parameters relating to the correlations, which a thermal-hydraulic system code is built upon, the quantification of uncertainties is not as straightforward.

The quantification of the uncertainties of thermal-hydraulic system codes has been the goal of the Post BEMUSE Reflood Models - Input Uncertainty Methods (PREMIUM) benchmark organized by OECD/NEA. VTT has been taking part in PREMIUM using APROS within The Finnish Research Programme on Nuclear Power Plant Safety 2011 – 2014 (SAFIR2014) UBEA project. The specific focus of the PREMIUM benchmark is with closure equations relating to reflooding since most of the phenomena these correlations describe cannot be separated in experimental setups from other phenomena. [5]

In the PREMIUM benchmark the quantification of the uncertainties was performed with the help of experimental data from the German FEBA tests performed in the 1980's [6] and verified with the French PERICLES 2D tests also performed in the 1980's [7]. Within the UBEA project a similar quantification of the uncertainties of APROS was performed with data from the Finnish VEERA reflooding experiments performed in the 1990's as a joint task between Lappeenranta University of Technology and VTT.

The methods used by VTT for the quantification were the same as during the PREMIUM benchmark, FFTBM (Methodology for characterizing the range of input uncertainty parameters by the use of the Fast Fourier Transform Based Method) [8] and CIRCE (Calcul des Incertitudes Relatives aux Corrélations Élémentaires, English: Calculation of the Uncertainties Related to the Elementary Correlations) [9]. The intent was to provide results that can be compared to assess the functionality and reliability of the methods.

In this paper the quantification of the uncertainties of the parameters is presented along with some comparisons to the results VTT achieved in PREMIUM. First the VEERA facility and the APROS model of it are presented, followed by the determination of the parameters influential in the simulations of the reflooding experiments. Thereafter an analysis with the two different methods to quantify the uncertainties based on the VEERA reflooding experiments is produced, and finally the results of the quantification are compared to the ones reached in the PREMIUM benchmark.

2. VEERA FACILITY AND APROS MODEL

The VEERA facility was originally built in 1987 to investigate the effects of boric acid injection in the upper plenum of a PWR reactor during a LOCA situation. The reference reactor type that was simulated was the VVER-440 in use in Loviisa, Finland. The facility has been modified two times, first in 1988 to investigate boric acid effects in the lower plenum, and second in 1993 for reflooding experiment purposes. [10]

In the reflooding setup the facility consisted of a downcomer, lower plenum, core inlet tube, test section with electrically heated rod simulators, core outlet throttle, upper plenum, moisture separator and a condenser. After the condenser the steam was led directly to the building roof. Special care was taken in simulating the structures immediately above the test section accurately, namely the core outlet throttle. To prevent oscillations between the test section and the downcomer a blind disk was installed in the lower part of the downcomer, which prohibited water from moving up the other side of the U-tube. A schema of the facility can be seen in Fig. 1.

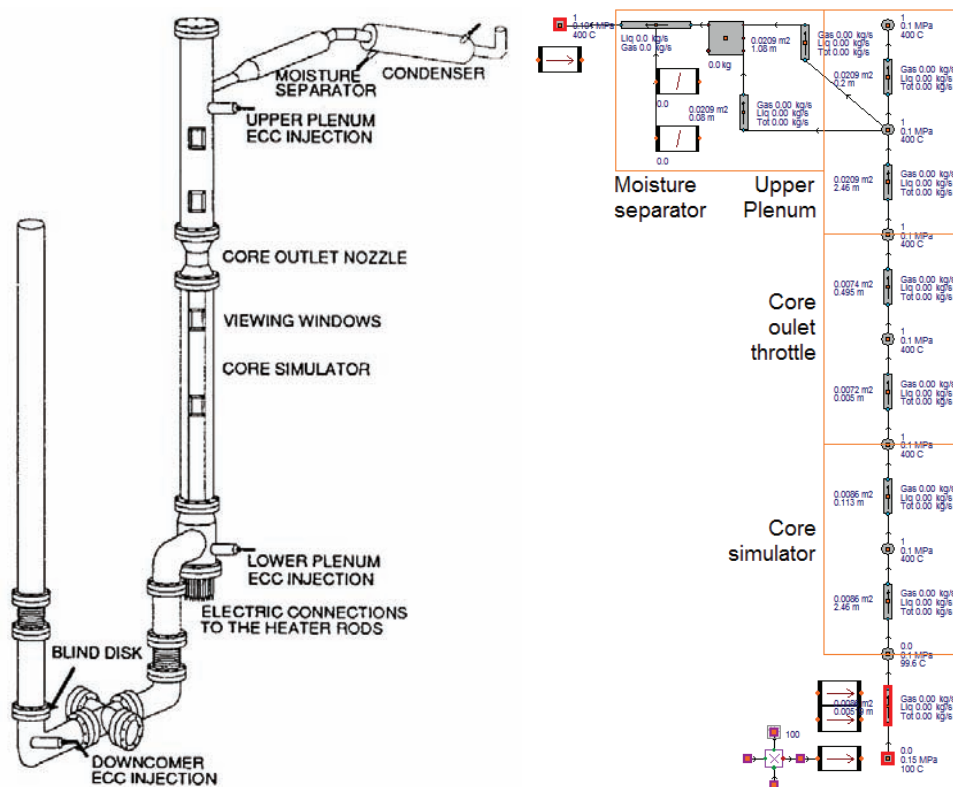


Figure 1. On the left: A schematic picture of the VEERA facility in the 1993 reflooding setup. The lower plenum ECC injection is directed at the core inlet tube just below the heated section [10]. On the right: The APROS model of the VEERA facility in reflooding setup.

The test section houses a hexagonal arrangement of 126 heated rods and one unheated rod in the center. The facility is in full scale compared to the reference reactor and simulates one full rod bundle. The heated part length is 2.42 m, which is divided into nine power steps following a cosine distribution. The rods are kept in place by eleven grid spacers, the last one of which is at the top of the heated length.

The rods have a diameter of 9.1 mm with a 1 mm thick stainless steel cladding and a nichrome heating coil wound inside magnesium oxide insulation. The opposing walls of the hexagonal shroud are at a distance of 139 mm from each other. The facility is insulated with 100 mm mineral wool, excluding viewing windows in the test section, which were originally intended for observing boric acid effects. The windows cover only a small area compared to the whole test section. Additionally, the housing can be heated separately of the rods to create desired initial conditions.

The APROS model of the VEERA facility consists of a core simulator with the test section inside, core outlet nozzle, upper plenum and moisture separator. The model can be seen in Fig. 1. The core simulator consists of an APROS built-in pipe element with 54 calculation nodes inside for the heated length. Each node is connected via a heat transfer module to a heater rod outer node. The spacer grids are realized with an additional form loss coefficient of 1 in the thermal hydraulic nodes at the heights of the spacer grids. In the reflooding calculations rod temperatures are imposed on the heat structures according to experimental measurements at the start of the water entering the heated section.

Above the heated length there are no heat structures, but only pipe elements with appropriate flow areas and hydraulic diameters set according to the VEERA facility specifications. The moisture separator

consists of two pipes, a node with a specific shape and an outlet branch. The node, which is very thin in the bottom and larger in the top, is assumed to be fully separated into gas and liquid phases. A form loss coefficient of 15 has been set in the outlet branch, defined in the validation phase of the model by matching upper plenum pressure to experimental results. Momentum is not carried over the moisture separator.

One of the pipes connecting the separator node to the upper plenum is connected to the bottom of the node and the other one to the top. The node bottom is set higher than the point in the upper plenum. The dimensions of the pipes are larger than in the real facility – the flow area in both pipes is the same as in the upper plenum – to allow all liquid entering the moisture separator to flow back into the upper plenum. This is the most likely scenario in the experiment, although no data exists to prove or disprove it.

2.1. Initial Reflooding Simulation Results

To compare the simulation results with experimental results two reflooding experiments were calculated with APROS. The experiments were chosen due to being the ones which take the longest time to quench providing more spread for comparison of values. Fig. 2 presents selected inner cladding temperatures and collapsed water level for the height of the facility for one of the experiments.

According to Fig. 2 the water mass balance in the test section of the VEERA facility is well reproduced in the calculations. The sharp drops in the calculated collapsed water level after approximately 120 s are probably caused by a large quantity of water entering the moisture separator and falling back into the upper plenum momentarily after. Essentially it is numerical noise. The constant increase in water level after approximately 150 s on the other hand is the result of the rods fully quenching as evident from the cladding temperatures and thus the test section being completely filled with liquid water.

The cladding temperatures are also well reproduced in the beginning of the water injection with the exception of temperature at elevation 1035 mm dropping too fast in the calculations. The rod quenching times on the other hand are not in agreement with the experimental cladding temperature curves because they quench a lot earlier than the calculated ones and in a more abrupt manner. The behavior of the collapsed water level measurement in the experiment suggests that even in the end of the experimental

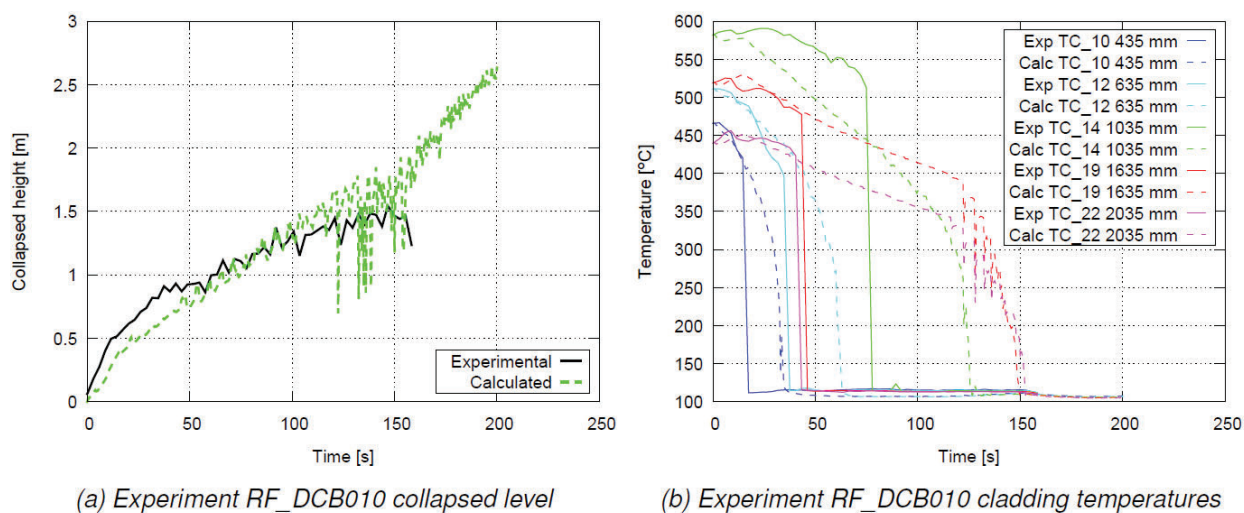


Figure 2. Comparison of experimental and calculated values of collapsed water level and inner cladding temperatures for VEERA reflooding experiment 10.

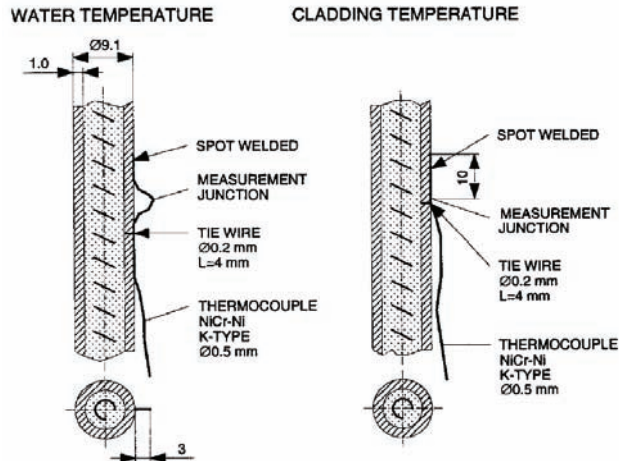


Figure 3. Attachment of the thermocouples on the heater rods. [10]

data the rods have not quenched. This implies that there appear to be issues with the cladding temperature measurements, which signifies that the quench front progression cannot be deduced from them.

The thermocouples used for the temperature measurements have been soldered and/or tied onto the rods. Fig. 3 depicts the different methods of attachment of the thermocouples. The accuracy of the thermocouples, per se, is approximately ± 2 °C. However, the positioning of the thermocouples in relation to the object of the measurement affects the accuracy. In the case of the coolant measurements the thermocouples are surrounded by the object of the measurement all around and thus accurately portray the temperature of the object. In the case of the cladding temperatures the thermocouples are situated on the boundary between the cladding and the coolant. Additionally, in a dynamic situation, such as reflooding, water droplets fly around and cladding temperatures depend heavily on whether film boiling is still occurring or not. Thus the thermocouples may cool below film boiling temperature due to the droplets faster than this happens to the cladding. If the heat flux from the cladding to the thermocouples is not large enough to heat the thermocouple again the thermocouple will not portray the temperature of the cladding.

In the lower parts of the test section the violent boiling may cause thermocouples at a certain height above the quench front to quench before the rods. At the top of the heated section the experimental quenching times behave irregularly implying that water carried by the rampant steam production quenches the thermocouples when hitting them at a random time. Similarly in the calculated curves the effect of the water dropping back to the heated section from the upper plenum can be seen as sharp drops in temperature before final quenching at elevations 1635 mm and 2035 mm as portrayed in Fig. 2.

In the case of some experiments the sharp staircase-like drops in the calculated temperatures start before the final quenching in the experimental data, although the calculated quench occurs after this. This sporadic behavior poses difficulties to the FFTBM and even more so for the CIRCE methods for quantifying the uncertainties of the inputs, because they both rely on analyzing the differences in the calculated values based on small changes in the inputs.

3. IDENTIFICATION OF INFLUENTIAL PARAMETERS

The identification of the influential parameters that would be quantified was performed similarly as in the PREMIUM benchmark [11]. In PREMIUM VTT varied each parameter according to a predefined

variation range and the results were compared to each other and to the best-estimate run with nominal, or best-estimate (BE), parameter values. The output parameter that was used was cladding temperature at the hottest measured point in one experiment including quenching time extracted from the temperature curve.

The criteria used in the PREMIUM benchmark with the FEBA experiments to determine whether a parameter was influential needed to be adjusted according to the differences of the VEERA experiments. Most importantly quenching times could not be taken into account due to large differences between experimental and calculated values, which were in turn most likely caused by an inappropriate way of attaching the thermocouples to the heater rods leading to thermocouples quenching before the cladding.

Because the VEERA experiments are much faster than the FEBA experiments the criteria used to determine influence, a minimum difference of 50 °C of the variation runs to the best-estimate run in PREMIUM, was changed to 25 °C. Additionally to rule out spurious effects, where both negative and positive change in the input parameter would cause change in the same direction, the maximum difference between the negative and positive increment runs was required to be at least 50 °C.

Two experiments were used in the identification of the influential parameters of the VEERA calculations. The output parameter that was considered was at approximately middle elevation of the bundle, which was the hottest measurement point out of the five points used in the analyses and at the same time the one that took most time to quench. Similarly as in the FEBA analysis, in the case of the VEERA experiments the temperature curves were cut right before the quenching occurred in the experimental results.

The final list of the parameters identified as influential was *minimum film boiling temperature, interfacial friction droplet, wall friction coefficient / liquid, heat transfer between gas and interface, heat transfer to dry wall / forced convection to gas and additional heat flux near quench front*. These are all the same parameters that ultimately were identified as influential by VTT and the uncertainty of which was quantified in the PREMIUM benchmark analyses [8].

4. FFTBM ANALYSIS

The application of the FFTBM methodology was conducted similarly as for the FEBA experiments in the PREMIUM benchmark, with VTT's Python scripts built for the purpose [8]. Namely the error function that was used was the shortest distance of each experimental point from the calculated points, taking into account both magnitude and time variation, and all of the 15 experiments used in the analyses were used at the same time to define the global average amplitude value for each variation of the input parameters. The workflow for the application of the FFTBM methodology as described by VTT in [8] is as follows:

1. Run reference case
2. Select output parameters
3. Derive all the $AA_{R_i}^{REF}$
4. Select uncertain input parameter
5. Run sensitivity cases for the input parameter
6. Derive all the $AA_{R_i}^{*,IP}$ (one per output parameter) and the $AA_G^{*,IP}$ (one per sensitivity calculation)
7. Define threshold value and identify the variation range
8. Discard input parameter, if it is not relevant

The sensitivity runs were also performed in the same fashion as before by running seven simulations with each input parameter from the lower limit of the range to the higher limit at evenly spaced intervals. The sensitivity runs were performed for all experiments for all parameters after which the results were

aggregated to produce the global average amplitudes for each variation. All five cladding temperature curves as defined in the identification phase were used in the aggregation.

Fig. 4 presents the FFTBM analysis results with the nominal value for each parameter set at 1. According to the figures the nominal value is not the best value for any of the parameters. This in turn would require a new iteration of the analysis to be performed with new nominal values. It was already discovered with the FEBA experiments that iterating the FFTBM method was not a viable way of reaching a convergence of the results and that a better form to find the optimal nominal values would be with trial-and-error, CIRCE or expert judgment [8]. In fact after the CIRCE application, the results of which are presented in the next chapter, was completed, an FFTBM analysis was performed with the new nominal values for the parameters. The results of the analysis are portrayed in Fig. 5.

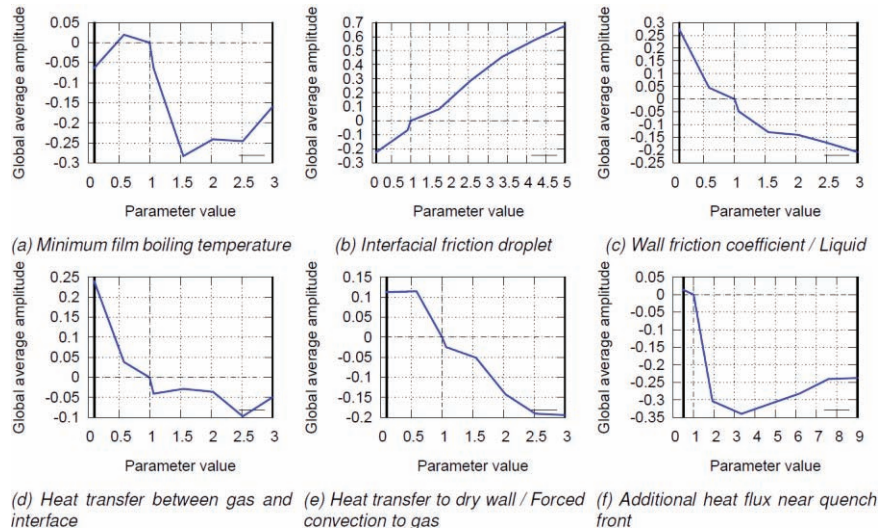


Figure 4. FFTBM analysis results for the different input parameters. The black vertical lines define the ranges of the variation.

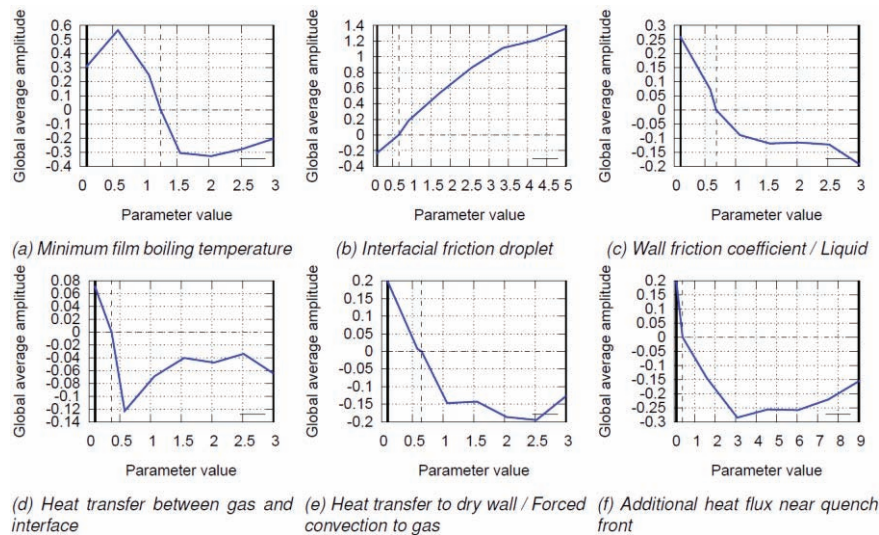


Figure 5. FFTBM analysis results for the different input parameters with nominal values defined with the following CIRCE analysis. The black vertical lines define the ranges of the variation.

It is evident from comparing Fig. 4 and Fig. 5 that even after defining new nominal values, which are supposed to produce a better best-estimate run, the FFTBM method does not produce usable results in the case of the VEERA experiments. The forms of the global average amplitude curves are very similar to the original FFTBM analysis and the optimal values of the parameters specified with the new analysis do not coincide with the values defined in the CIRCE analysis.

5. CIRCE ANALYSIS

The workflow of the CIRCE method as described by VTT in [8] is as follows:

1. Select uncertain input parameters
2. Run sensitivity and best-estimate runs
3. Choose output points
4. Derive all the $\frac{\partial R_j}{\partial \alpha_i}$ (per j output points and i input parameters)
5. Create CIRCE input file and run CIRCE
6. Check the residuals and remove unfit output points, if required
7. Run sensitivity calculations to determine that hypothesis of linearity is met and whether linear or log-linear formulation is better
8. Transform the bias results, b_i , to input parameter distributions, p_i
9. Check that new best-estimate runs with biases produce better results
10. Check that for example 93 randomly varied runs envelop about 95 % of experimental output points (BEPU analysis)

The application of the CIRCE method for the quantification of the uncertainties was performed in a somewhat different manner compared to the PREMIUM analysis. Because the quenching phase was excluded from the analysis, as large amount of data points as possible was used to provide the input for CIRCE. The original idea was to use all available data points, but because the CIRCE program only allowed 500 points every second data point from each experimental curve was used. The data points at 0 seconds, which was the initial state of the model, were also excluded. Choosing between the different points for example based on the formation of the derivatives used by CIRCE could be arbitrary and thus the idea was to use as much information as possible.

This on the other hand caused some practical issues, because there were 373 data points to analyze from the 15 experiments. Consequently the same time frame around each point and the same parameter increments were used for all points, which in turn caused some of the derivatives to be badly formed. I.e. the best-estimate run values would not be in between the positive and negative increment run values. The time frame was chosen as ± 1.3 seconds and the increments as approximately ± 10 % of the calibrated best-estimate values at each iteration.

Another difference to the previous CIRCE analysis was that at each iteration new derivatives were calculated; with each iteration all experiments were calculated 13 times to provide positive and negative increment runs and the calibrated best-estimate run. Also, with each iteration the CIRCE analysis was performed with all data points and based on the analysis of the residuals some points were removed. In a total of 11 iterations 65 different points were removed of which 39 only appeared once, 17 appeared two to five times and 9 appeared seven or more times. On average 16 points were removed in each iteration constituting 4.3 % of all points.

Because the derivatives were calculated for each point with each iteration, the removal of different points in different iterations does not cause problems. In essence each previous iteration served as a hint of where to look for a better set of best-estimate values and the results of each iteration stood up on their

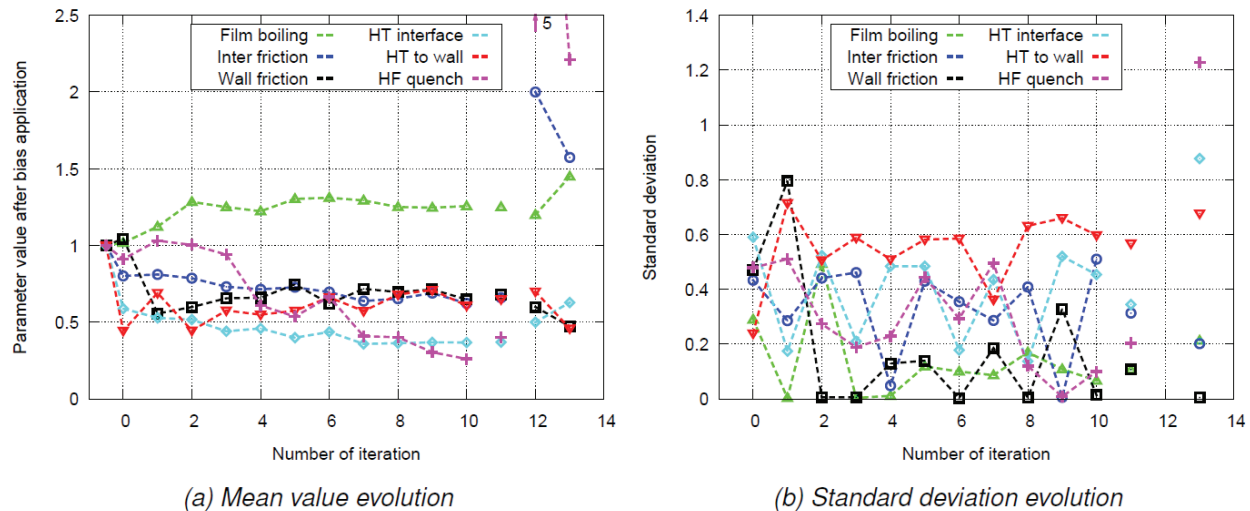


Figure 6. Results of the CIRCE iterations, where at point -0.5 on the x-axis are the nominal values and at 0 the original CIRCE application results. At point 10 are the results of the last CIRCE application and at 11 the final chosen calibrated mean/best-estimate and standard deviation values for the parameters. Another CIRCE application was performed using the calibrated values from the PREMIUM benchmark as the starting values for the parameters, which is shown at point 12, and the result of which at point 13.

own. Furthermore due to the nature of the simulations – where a small difference in an input parameter may cause chaotic behavior – different data points may suffer from this erratic behavior and be unusable with each iteration. This of course begs the question of whether the CIRCE method works with the VEERA experimental data in general. Fig. 6 presents the results of the iterations.

The CIRCE results show a partial convergence in the course of the iterations; most mean values hover around their average and the standard deviations also, although the standard deviations fluctuate more. Four of the parameters converge at values close to the ones determined in PREMIUM (which can be seen in the figure at point 12 on the x-axis) while two parameters were defined values in PREMIUM which were several times as large as the ones defined this time. The trial iteration from x-axis point 12 to 13 also proves that the values reached in PREMIUM are not a local optimum which could be reached with the VEERA experimental data.

The two parameters differing from previous results, *interfacial friction droplet* and *additional heat flux near quench front*, are also parameters, which affect the VEERA simulations mainly in the quenching phase. Because quenching times could not be included in the analysis, like they were in PREMIUM, a difference in the results can be expected.

The final definition of both mean values and standard deviations was performed through averaging over the last five iterations. In the case of the mean values more focus was put on the last values in case convergence was evident. The ranges of variation were chosen at 2-sigma distance of the mean values either on a linear or logarithmic scale depending on which one would produce larger distance. The final results of the CIRCE iterations are listed in numerical form in Table I.

The PDF types in the final PDF formulation are based on sensitivity runs. A visual comparison of the results in logarithmic and linear scale was performed and the one behaving more linearly was chosen. During the CIRCE iterations parameter *wall friction coefficient / liquid* was considered as following a

Table I. Final results of the CIRCE iterations to define the input parameter probability distribution functions. The mean values are the same as the calibrated best-estimate (CBE) values on a linear scale, while they are reported according to the PDF type. Similarly the standard deviations are reported in their respective scales, whereas the minimum and maximum values are on a linear scale for all parameters.

	Minimum film boiling temperature	Interfacial friction droplet	Wall friction coefficient / Liquid	Heat transfer between gas and interface	Heat transfer to dry wall / Forced convection to gas	Additional heat flux near quench front
PDF	normal	log-normal	normal	log-normal	normal	normal
CBE	1.25	0.66	0.68	0.37	0.65	0.4
Mean	1.25	-0.42	0.68	-0.99	0.65	0.4
Stdev	0.11	0.31	0.11	0.35	0.57	0.2
Min	1	0.05	0.45	0.05	0.05	0.05
Max	1.55	1.3	0.9	1.1	2	0.8

log-normal distribution, but after defining the final ranges it was deemed to follow a normal distribution. Because of the iterative procedure and redefining the derivatives with each iteration, this does not pose any problems.

The ranges of the parameters' sensitivity runs were chosen to be the same as the final ranges of the PDFs, except for parameter *additional heat flux near quench front* for which the whole range of variation was used. This is due to the final range being so small compared to the variation range for the FFTBM application – which is where the data is from – that only one point would have fit inside the range allowing no conclusions of the linearity of the parameter. Thus the larger range, which clearly shows linear-scale variation, was selected.

To check how well the quantification of the input parameters' uncertainty was accomplished BEPU analysis was performed. The 15 experiments used in the quantification were each simulated 93 times with randomly selected parameter values according to the defined PDFs to provide 95 %/95 % uncertainty bounds. Fig. 7 (on the left) presents the bounding limits for all the 373 data points used in the analysis highlighting the 65 points that were removed in different stages of the iterations for the VEERA PDFs.

The bounds portrayed in Fig. 7 (on the left) cover the experimental values for the most part. 23 of the lower limits, the 2.5 % values, are above the experimental values, while 66 of the higher limits are below the experimental values. Taking into account the 65 points, which were removed at some CIRCE iteration, the numbers are lowered to 7 and 38 respectively, constituting approximately 10 % of all of the points.

According to the BEPU analysis definition 95 % of the experimental data points should be covered by the calculated bounds with a certainty of 95 %, but only 90 % are covered, although the definition of the 95 % certainty of covering the points leaves room for random error. Still, most likely the PDF definitions are not perfectly formed, nor should they be expected to be, since the application of CIRCE did not follow the instructions to the point. As such the PDFs are acceptable and although more work could be performed to refine them so that the BEPU results would cover all 95 % of the experimental points it was not deemed appropriate for the purposes of this study, which was to experiment on the different methods to define the uncertainties. To this end only qualitative agreement between the calculated bounds and the experimental points was required.

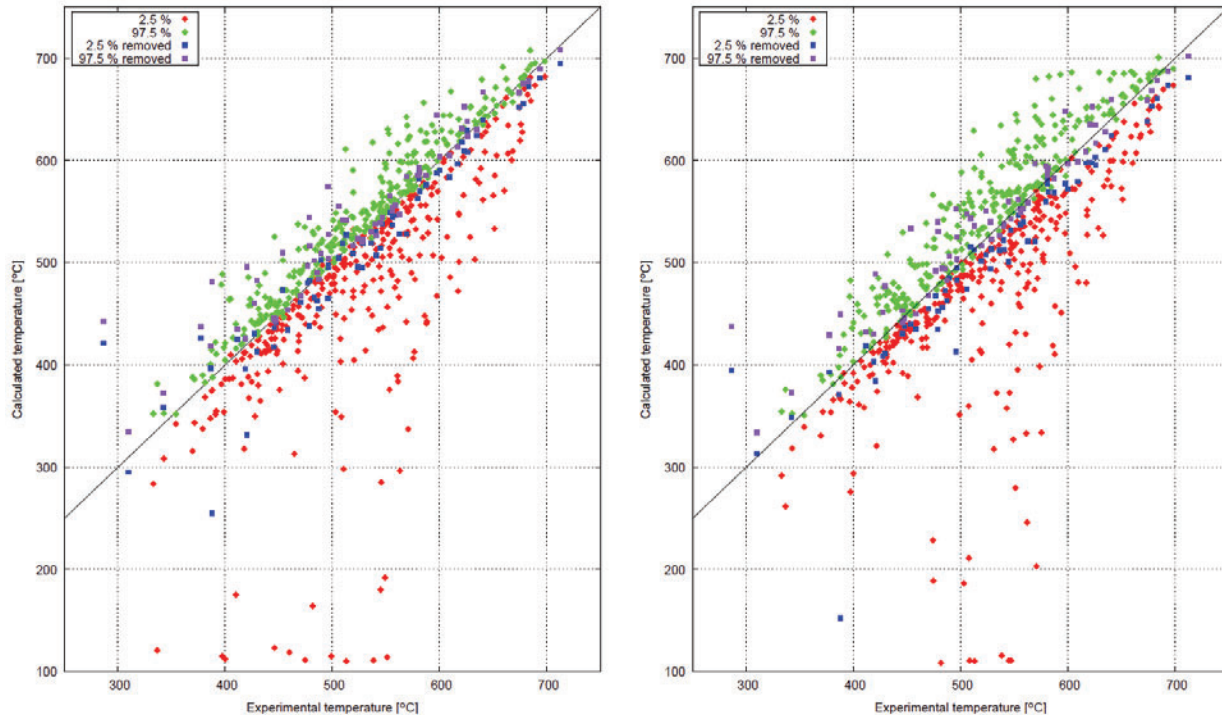


Figure 7. The 2.5 % and 97.5 % uncertainty limits for all the 373 data points used in the CIRCE analysis in relation to the experimental values calculated with the VEERA PDFs (on the left) and PREMIUM PDFs (on the right). The black line represents a perfect fit between experimental and calculated temperature.

6. COMPARISONS TO PREMIUM

To try to deduce whether the quantification of the uncertainties with the VEERA data was successful comparisons of the results to the results obtained in PREMIUM were performed. A direct comparison of the PDFs defined with the VEERA analysis to the PDFs defined with the PREMIUM analysis is presented here. The PDFs from both analyses are shown in graphical format in Fig. 8.

In the previous chapter it was briefly mentioned that for four of the six influential parameters the calibrated best-estimate values were close to each other in the VEERA and PREMIUM analyses. This is evident in the numerical, as well as the graphical presentation of the PDFs. In the case of the two parameters, for which the calibrated best-estimate values did not fit, *interfacial friction droplet* and *additional heat flux near quench front*, the variation ranges do not even overlap and the distributions are narrower in the case of the VEERA analysis in general.

Three of the four parameters with similar mean values are also narrower in the VEERA analysis than in PREMIUM. For the two with normal distributions the standard deviations are approximately 40 % of the PREMIUM deviations. For the third with log-normal distribution the standard deviation is approximately 36 %, but because of the PDF type the distributions overlap more than in the case of the parameters with normal distributions.

The fourth parameter with a similar calibrated best-estimate value differs from all the other parameters in the sense that the distribution defined in the VEERA analysis is wider than the distribution defined in the PREMIUM analysis. For the parameter in question, *heat transfer to dry wall / forced convection to gas*,

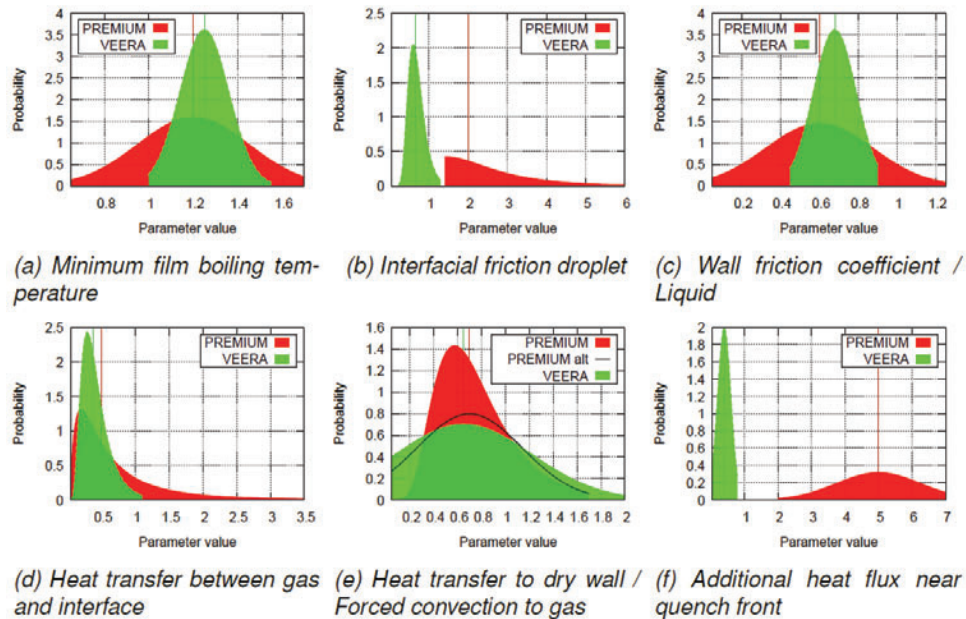


Figure 8. Graphical comparison of the PDFs defined in the PREMIUM benchmark to the PDFs defined with the VEERA data. The vertical lines portray the mean values of the PDF definitions. In figure (e) an alternate definition for the PREMIUM PDF with a normal distribution is included.

the situation is different, though, because a log-normal distribution was defined for it in the PREMIUM analysis and a normal distribution based on the VEERA data.

In the PREMIUM analysis the choice between a normal or log-normal distribution based on the sensitivity runs was almost arbitrary for the parameter *heat transfer to dry wall / forced convection to gas*. In fact either formulation could have been used, but log-normal was chosen based on the final FFTBM analysis and the GAA form. Still, even considering a normal formulation the PREMIUM distribution would have been narrower (standard deviation of 0.5 compared to 0.57) due to the smaller upper limit of the range, which was the basis of the standard deviation in the PREMIUM analysis. Although, as shown in Fig. 8e, the differences in the PREMIUM and VEERA PDFs would be very small had the normal formulation been used in PREMIUM.

In summary, excluding the parameters *interfacial friction droplet* and *additional heat flux near quench front*, the mean values of the PDFs defined for the parameters in the two analyses agree with each other, while the standard deviations are in general smaller. But as the standard deviations were defined through an FFTBM based analysis in PREMIUM and through CIRCE in the VEERA analysis differences are to be expected.

The PREMIUM analysis focused on actually fitting the experimental points inside the 95 %/95 % limits and achieved this through test runs. In the VEERA analysis the standard deviations came directly from the CIRCE application, although expert judgment was used in the form of averaging the deviations over several iterations. In so doing the VEERA analysis did not actually even rely directly on the CIRCE methodology.

Also during the PREMIUM benchmark it has been noted that CIRCE produces narrower ranges than FFTBM [12]. This is assumed to be caused by CIRCE optimizing the PDFs as a whole to encompass only 95 % of the experimental points and not all of them. FFTBM on the other hand only handles one

parameter at a time, which can lead to the same uncertainty being assigned to several parameters and thus wider ranges than would be necessary. Because of this it can be expected that the PREMIUM ranges are wider than the VEERA ranges.

To compare the PDFs further BEPU runs of the same 15 VEERA experiments as used in the VEERA analysis were performed with the PREMIUM PDFs. Fig. 7 portrays the results of the BEPU runs with both PDFs side by side for comparison for all the 373 data points. A visual examination of the figures reveals that the upper limits of the data points are spread out higher for the PREMIUM PDFs than for the VEERA PDFs, while the lower limits behave quite similarly in both. In general the differences are not that large though. For the VEERA PDF BEPU runs 7 of the lower limits are above the experimental values, while 38 of the higher limits are below the experimental values, when taking into account the 65 points that were removed. In the case of the PREMIUM PDFs the same numbers are 4 and 35, which is only a marginally better result of enveloping the data points even with much wider PDFs.

7. SUMMARY AND CONCLUSIONS

The purpose of the work was to evaluate the current means by which the uncertainties of the constitutive equations of APROS could be quantified. If possible, the work was supposed to contribute to the task of actually quantifying the uncertainties, which could then be used in BEPU studies with APROS by all its users. In this form the uncertainties would be a part of APROS validation and verification providing a standard tool for analyses with APROS.

Yet several issues arose during the quantification process. The most important problems related to the rapid quenching of the cladding, which could not be duplicated with the simulations and caused the quenching phase to be dismissed in the quantification analyses.

The quantification of the uncertainties was started with a FFTBM analysis performed in a similar manner as in the PREMIUM benchmark. The results of the analysis were not usable. No better results were reached even when another attempt was made by setting the best-estimate parameter values to the ones defined by the CIRCE analysis, which was the process that was used for the final quantification of the parameter uncertainties in PREMIUM.

The CIRCE method was applied in a partly different manner compared to the instructions provided by CEA: a very large amount of experimental points was used and with each iteration the derivatives were calculated again, instead of only the calibrated best-estimate run. Due to an automatized way of defining the derivatives some of them were badly formed, but the idea was that they would turn to noise in the CIRCE process, while the proper information would define the results.

Considering that the CIRCE iterations behaved fairly well the assumptions made about the process seem to have been at least not harmful to the successful application of the methodology. The parameters more or less converged during the iterations with four out of six converging to values close to the ones in PREMIUM. The other two were ones that have most of their impact on rewetting, which was not taken into account in the analyses. The widths of the uncertainty bands were also found to be slightly narrower than with the PREMIUM PDFs and the amount of CIRCE data points covered lower when comparing the BEPU analyses. The difference was not very significant.

Taking into account the large differences in the PDF definitions larger differences in the BEPU analysis results could have been expected. The fact that the differences are small compared to the width of the uncertainty bands and the CIRCE points are covered almost equally is quite remarkable, because it could be thought that wider PDFs cause wider uncertainty bands. Of course the two parameters, the PDFs of which did not even overlap, could have had unexpected results.

This goes to say that the parameters are not independent and do not necessarily behave linearly, which are two main assumptions when applying CIRCE. Another point to make is that the process of defining the PDFs was different in the VEERA analysis to the one used in PREMIUM and that the same process did not work in the other one. Also, even in the VEERA analysis where CIRCE turned out to be the only method providing sensible results, the PDFs could not be read directly from the results, but expert judgment was required.

The issues ran into in the use of FFTBM and CIRCE in VTT analyses imply that not only is more work required to widen the basis for the quantification of the uncertainties, but also more research to advance the methodologies and their use is necessary to reduce the amount of expert judgment required.

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