A VALIDATION OF WESTINGHOUSE MECHANISTIC AND EMPIRICAL DRYOUT PREDICTION METHODS UNDER REALISTIC BWR TRANSIENT CONDITIONS

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ABSTRACT

Dryout correlations are commonly used to predict the critical power in BWR fuel rod bundles under both steady-state and transient conditions. Even though these correlations can be based on mechanistic features, they are still essentially empirical and require the use of an extensive and fuel-specific critical power database to be developed. By contrast, mechanistic methods based on sub-channel annular two-phase flow modeling have the potential for accurate dryout prediction capabilities outside the development database.

MEFISTO-T is a transient sub-channel analysis code, developed at Westinghouse, designed to mechanistically predict the dryout event in fuel rod bundle under BWR steady-state and transient conditions. The code uses a multi-field approach where the steam, drop and film fields are treated separately in every sub-channel. Several film fields are considered to model one film per rod/wall surface in every sub-channel. The code has been previously validated under a wide range of BWR steady-state and transient conditions [1].

The dryout experiments from the Studsvik/FIX-II facility have been used in this work. These tests provide realistic experimental information regarding typical fast pressure increase transients in a BWR core. The available steady-state dryout database was first used to adjust the grid effect in MEFISTO-T and to develop an empirical dryout correlation. The transient dryout experiments were then simulated and the measurements were compared to the predictions from both MEFISTO-T and the dryout correlation.

The results show that the MEFISTO-T code yields a best-estimate prediction of the transient dryout, while the dryout correlation yields a robust but slightly conservative prediction. This confirms the validity of the current approach used at Westinghouse to develop robust and slightly conservative transient CPR correlations.

KEYWORDS
Dryout, Film flow analysis, CPR correlation, Transient, BWR fuel

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1. INTRODUCTION

One of the most important limitations of Boiling Water Reactors (BWR) fuel is the margin to critical power, which must always be controlled under nominal operating conditions and Anticipated Operational Occurrences (AOOs). The critical power refers to the fuel bundle power at which a rapid degradation of the heat transfer occurs, generally due to the disappearance of the liquid film in annular two-phase flow. This phenomenon is called dryout. Dryout on a fuel rod leads to an undesirable increase of temperature which can damage the cladding, thereby challenging the fuel structural integrity. Safety criteria are in place to prevent the dryout phenomena to occur under both steady and transient (AOOs) BWR operations. The critical power is therefore an important parameter which must be accurately predicted in order to calculate the thermal performance of the fuel rods and the margin to the fuel licensing criteria.

In BWR safety analysis, the thermal-hydraulics of the reactor core is typically simulated using parallel one-dimensional channels for each assembly. The margin to dryout power is often measured using the Critical Power Ratio (CPR) concept, which is the ratio of critical power to the operating power. The dryout power is calculated iteratively using a critical quality (x_{crit}) correlation which is developed based on an extensive steady-state, bundle-design specific, dryout database. The critical quality correlations are then verified to be conservative against transient dryout experiments. CPR calculation methods are typically (mostly) empirical which means that extrapolation outside the development database maybe challenging to justify, in particular in term of complex three-dimensional power profiles and application to realistic transients.

As a complement, or alternative, to empirical dryout prediction methods, detailed simulation of annular two-phase flow in rod bundle can be performed. Various sub-channel analysis codes are available to perform such simulations, e.g. COBRA-G [2], COBRA-TF [3]and MEFISTO-T [4], [5]. These codes model a fuel bundle as several inter-connected sub-channels where the one-dimensional mass, momentum and energy distributions are calculated. In the region where the two-phase flow regime is annular, the gas phase is considered using a continuous steam field and the liquid phase is considered using a drop field and one, or several, film field(s).The dryout prediction can hence be based on the simulation of the disappearance of the film flow, leading to heat transfer degradation. These codes still requires some empirical correlations in particular to simulate the exchange of mass, momentum and energy at the liquid film interface and hence validation is still needed. However, better and more physical extrapolation capabilities are expected and have been demonstrated [1].

In this paper, the performances of a dryout correlation form (used at Westinghouse) and the MEFISTO-T sub-channel analysis code are compared against the FIX-II fast pressure increase dryout database. Besides complementing the MEFISTO-T validation database [1], the aim of the study is to confirm the best-estimate transient dryout prediction capabilities of the MEFISTO-T code and quantify the conservatism of the empirical dryout prediction method.

2. EXPERIMENTAL DATABASE

The FIX-II project was an experimental work carried out by Studsvik Energiteknik AB in cooperation with AB ASEA-ATOM [6]. The aim of the project was to gain knowledge and improve the prediction accuracy of the consequences of certain transient accidents in Swedish BWR reactors. The whole project was composed of different kind of scenarios. Among them, the transient dryout tests [7] are of great interest to validate transient dryout prediction methods under realistic conditions. The main objective of the tests was to simulate events following fast pressurization transients in BWR reactors (e.g. turbine trip) with external and internal pumps.

Conditions were introduced to simulate the increase in power from pressurization in the reactor. The power transients were deliberately chosen so as to be severe enough to produce considerable periods of dryout. In the tests, special attention was directed to study the rewetting phase, which is expected to take place after the decay of power. The cladding temperature measurement on all rods at several elevations was collected. Dryout is assumed to occur when the temperature increases significantly (>10 °C/s) but it is more reliably detected by direct visualization of the temperature traces.

2.1. FIX-II Facility

The FIX-II loop includes a test section of 6x6 fuel rods with a heated length of 3.68 m, Figure 1. The fuel rods are simulated by conductive rods made of Inconel 600 (cladding) and Magnesium Oxide (pellet). The power released to the fluid is achieved by using direct current in the Inconel 600 cladding. The radial power distribution is also presented in Figure 1.

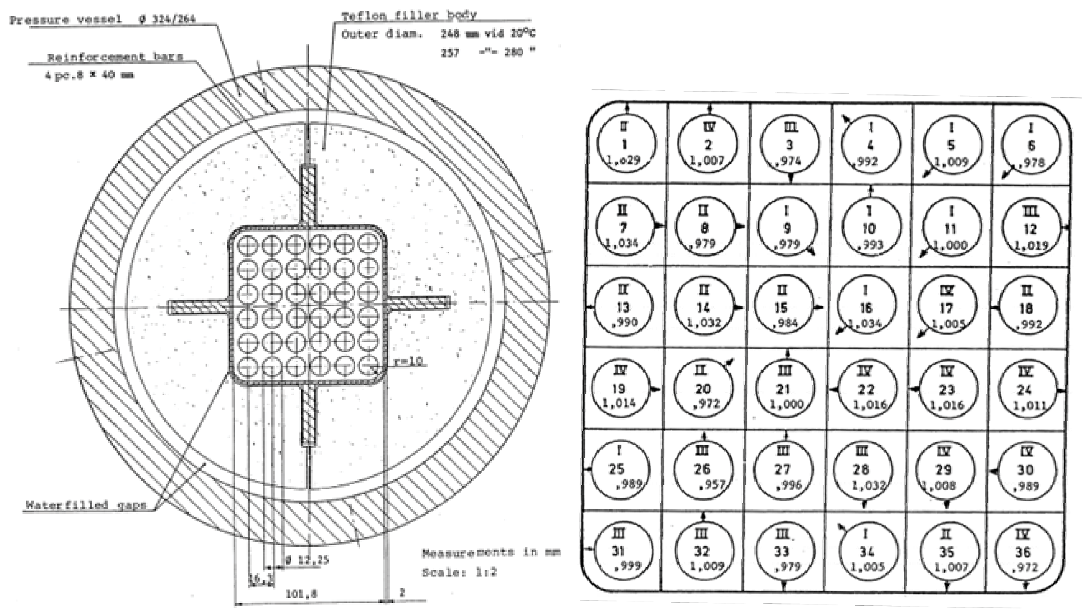


Figure 1. FIX-II test section (left) and rod radial power distribution (right)

The normalized axial power distribution can be seen in Figure 2. It was introduced by variations in the cladding thickness, while the outside diameter was kept constant.

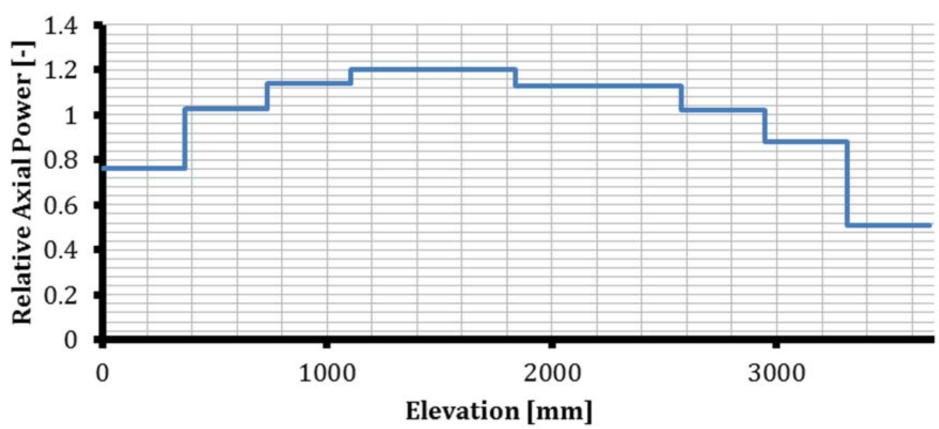


Figure 2. Axial power distribution

In each rod, there are five thermocouples to measure the cladding temperature. By a combination of four different patterns of thermocouple locations, cladding temperatures are measured at sixteen different axial levels.

2.2. Steady-State Tests

In order to get the most representative picture of the FIX-II bundle dryout capabilities, static dryout tests were performed, covering the power/mass flow range of interest. The FIX-II loop was operated at steady-state conditions at a pressure of 7.0 MPa and 10 C inlet subcooling, typical of BWR nominal operation. The pressure and inlet subcooling were maintained for all tests. For each test, a different power was selected and dryout conditions were obtained by decreasing the inlet mass flow rate. The resulting (critical) mass flowrate is plotted, as function of power, in Figure 3.

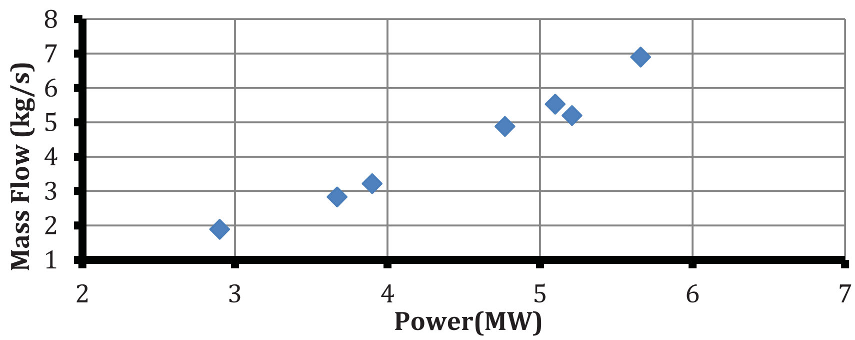


Figure 3. Mass flowrate vs. power at steady-state dryout conditions

2.3. Transient Tests

The objectives of the transient dryout tests were to collect transient dryout information from realistic pressure AOOs that might occur in the reactor (e.g. turbine trip). The initial conditions in pressure, power and mass flow rate correspond to typical nominal reactor values, scaled to the FIX-II 36-rod bundle. The transients are then initiated with positive ramps for the pressure and bundle power, before power decay and pump coast down begins. An example of boundary conditions can be seen in Figure 4.

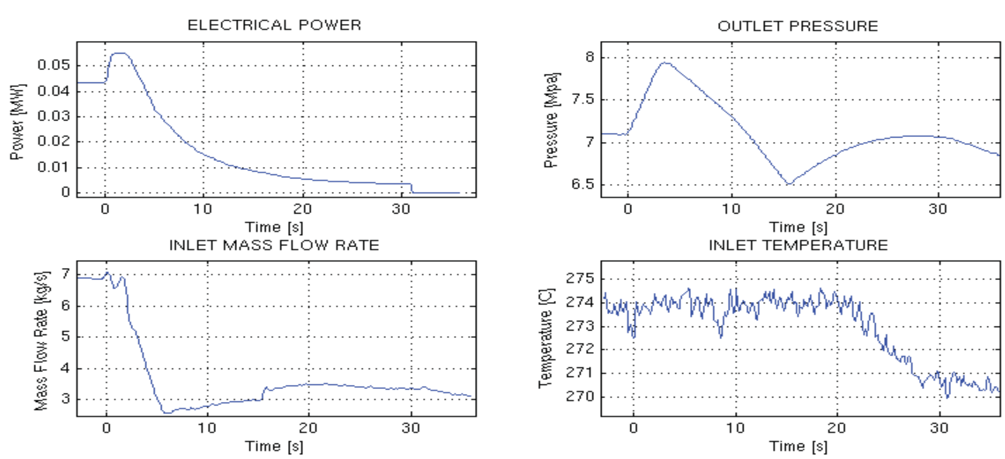


Figure 4. Boundary conditions (Example)

3. DRYOUT PREDICTION TOOLS

3.1. MEFISTO-T

MEFISTO-T is a transient sub-channel analysis code developed at Westinghouse with the main purpose to predict film flow distributions on every fuel rod during steady-state and transient operations [4], [5]. The code is based on a one-dimensional three-field approach where liquid film, liquid droplets and vapor are considered in every sub-channel. MEFISTO-T relies on a simplified two-phase flow model (VIPRE-W) to calculate the time-dependent distribution of flow and enthalpy in every sub-channels, before applying the three-field approach from onset of annular flow to bundle outlet, in all or selected sub-channels. VIPRE-W (based on VIPRE-01 [8]) was selected as the transient sub-channel driver code due to its high robustness, fast execution speed and accuracy under typical BWR operating conditions. The VIPRE-W two-phase flow model is based on a homogeneous 3-equation model with EPRI void fraction (herein referred as the "EPRI" model) or a drift-flux 4-equation model (herein referred as the "DRFT" model). Validation of the VIPRE-W sub-channel analysis code under steady-state and transient BWR conditions is documented in [9] and [10], respectively.

In the multi-film three-field approach, the film flow can be directly used as a local measure of margin to dryout. When the film flow is 0, dryout is assumed. The need for a critical film thickness (or flowrate) at dryout has been investigated but was considered unnecessary [4], [5]. Beyond dryout, one of the unique feature of the MEFISTO-T code is to continue the integration of the mass balance equations, so that to predict a negative film flowrate (similar to a CPR less than 1) to provide a consistent measure of the negative margin to dryout.

The selected drop entrainment and deposition correlation can be found in [11] Further information regarding the physical and geometrical models used by MEFISTO-T, including the drop deposition enhancement (due to spacer grids) correlation, can be found in [4] and [5].

3.2. CPR Correlation

A more classical method to predict dryout in fuel rod bundle is by using a one-dimensional approach to simulate the thermal-hydraulics of the fuel bundle along with an empirical dryout prediction model. In this method, dryout is typically predicted using the CPR concept. The CPR represents the ratio between critical power and nominal power. Dryout is predicted when CPR<=1, corresponding to the conditions where the nominal power is higher or equal to the critical power. The critical power is predicted using a critical quality correlation ($x_{critical}$) developed from available dryout data.

CPR correlations can be very accurate but, unlike the liquid film approach (Section 3.1), the method is empirical and hence has limited extrapolation capabilities outside the development database. It is used for thermal margin assessment in safety analysis. The dryout correlation which was used in this work has the same basis and form as the correlation used for Westinghouse latest BWR fuel product, SVEA-96 Optima3. Further information about this correlation can be found in [12]. In order to apply the correlation form to the FIX-II bundle, relevant empirical constants of the correlations were adjusted using the available steady state dryout tests.

This dryout correlation was used with both the Westinghouse safety analysis code, BISON, and the VIPRE-W code. BISON is a two-field, four equations, system code and is the standard code used for transient safety analysis at present at Westinghouse [13]; thus it was useful as comparison with the VIPRE-W/CPR performance. The comparison between the VIPRE-W/MEFISTO-T film flow solution and the CPR correlation is performed by considering the predicted minimum film flow per unit perimeter (MFF in unit of kg/s/m) and CPR-1. Both of these parameters yield 0 when dryout is predicted.

4. CODE CALIBRATIONS AND STEADY-STATE RESULTS

4.1. MEFISTO-T Calibration

The MEFISTO-T code relies on the sub-channel approach to account for crossflow effect within the assembly and on well-established mass exchange correlations developed in pipe applied at the sub-channel level. These mass exchanges correspond to liquid film evaporation, drop deposition to the liquid film and drop entrainment from the liquid film. However, the effect of grids needs to be accounted for by an additional model where the drop deposition is locally enhanced downstream of spacer grids with mixing vanes, due to increased turbulence. Details of this additional model are provided in [5] and [15]. The calibration of this model is typically performed based on a very small subset of the available steady-state dryout database [5] or could be done by comparison to dedicated CFD analysis [15], though this second approach is still under development. When calibrating this grid model, the amplitude of the local drop deposition enhancement needs to be adjusted so that to adequately predict the steady-state dryout power.

The calibration amplitude to the drop deposition enhancement is independent of thermal-hydraulics properties such as pressure or mass flow. It can however depend on how the sub-channels are arranged in the sub-channel model. Hence, this coefficient will have a different value for each one of the approaches discussed in Section 5.1.

The results of the MEFISTO-T calibration is illustrated in Figure 5, the mean MFF for all considered cases is nearly 0, no trend is observed with mass flow.

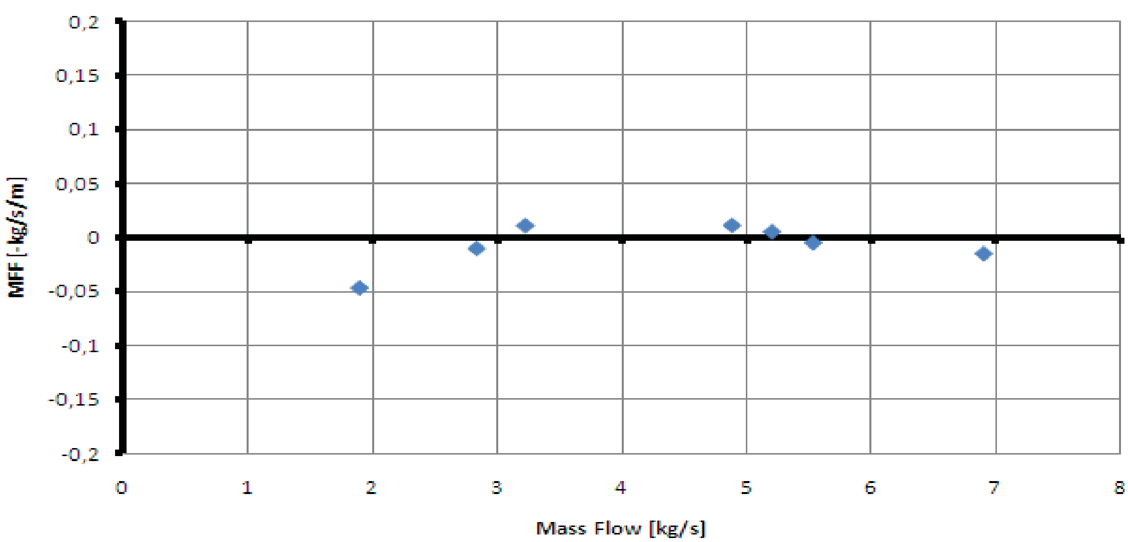


Figure 5. MFF prediction vs. mass flowrate for MEFISTO-T model for all steady-state experiments

One can observe how most of the MFF predictions are very close to zero, with the only exception of the first test, as it can be easily seen in Figure 5. Nevertheless, the value of mass flowrate in this test is very low (1.83 kg/s), well below the lowest flow value reached during the transient tests. Focusing on the rest of the results, it can be observed how the results of this calibration lead to excellent code prediction capability. The mean MFF is 9.17e-4 kg/s/m and the standard deviation is 0.0116 kg/s/m, corresponding to about 0.1% and 1.2% CPR error and standard deviation, respectively.

4.2. CPR Correlation Calibration

A typical CPR correlation form used at Westinghouse was used as a starting base (see section 3.2). Due to the limited nature of the available FIX-II database, only the coefficients regarding the overall dryout performance of the fuel bundle and the flow trend could be adjusted. Other effects (pressure, inlet subcooling, axial power, etc) could not be checked due to lack of available data, however these trends are well known and already captured adequately in the base CPR correlation form. The resulting calibration results are not presented in this paper, however they are very similar to the results obtained with the MEFISTO-T code.

5. TRANSIENT RESULTS

5.1. Model Sensitivity Analysis

The reference calculations with the MEFISTO-T code were performed using a typical subchannel-centered approach where all rods are considered individually and the subchannel connections are defined by minimizing all rod-to-rod and rod-to-box gaps, Figure 6.

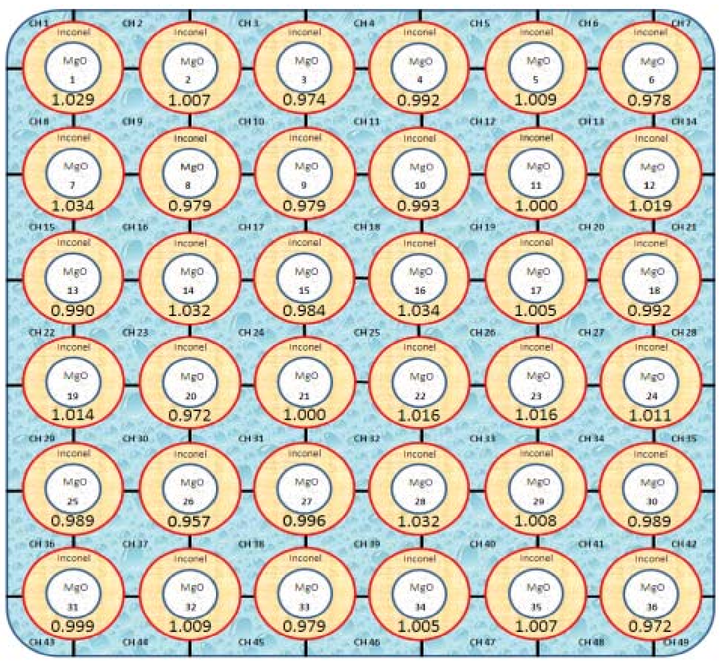


Figure 6. Sub-channel model (SCH) radial geometry

This is the most detailed approach that a sub-channel analysis can provide. However, the executing time to simulate a transient can be relatively long (as compared to the empirical CPR approach). In order to reduce the executing time, several simplified models were investigated in order to find a good compromise between prediction accuracy and computational time.

Four different simplified models of the 6x6 fuel bundle were considered and the simulation results were compared with the reference, detailed, model (in order of complexity):

- A single channel with a lumped (average) rod (“1CH Rod Model”)
- A single channel with a hot rod, all remaining rods are lumped together (“1CH 2 Rod Model”)

- A limiting sub-channel surrounded by 4 rods, all remaining sub-channels and rods are lumped together ("2CH Model")
- A 3x3 sub-channel model around the hot sub-channel, all remaining sub-channels and rods are lumped in 4 regions ("13CH Model")

As discussed in Section 4.1, the amplitude of the local drop deposition enhancement downstream the spacers needs to be adjusted. This step is performed for each geometrical model based on the available steady-state dryout data. After carrying out this adjustment, all FIX-II transient dryout tests were run for all the geometries. The dryout predictions for one of the tests are plotted on Figure 7.

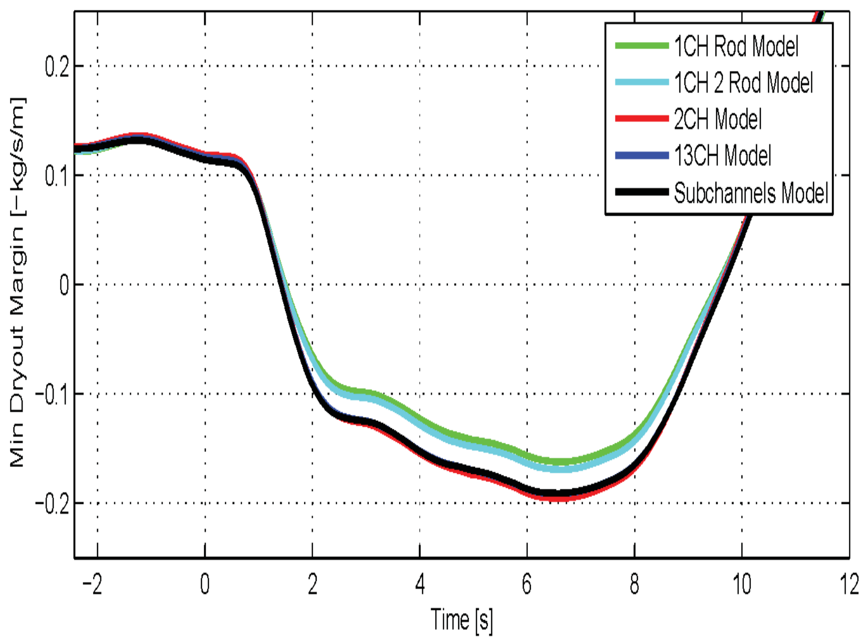


Figure 7. MFF predictions for all approaches for EXP6221

The results from "1CH Rod Model" and "1CH 2Rod Model" are significantly away from the reference. With a percentage of similarity around 60% for most of the cases, they cannot be considered as reliable. This was expected since the crossflow effect on dryout is significant and cannot be neglected. However, for "2CH Model" and "13CH Model", one can observe how the agreement with the solution from the sub-channels model is very good. The percentages of similarity are over 90 % for most of the cases, being slightly higher for the "13CH Model", as expected. Considering that the "2CH Model" is about five times faster than the "13CH Model" and 20 times faster than the complete subchannels model, it can be concluded that it is the best compromise between accuracy and computational time. Further investigation about this approach is recommended.

5.2. Comparison with Experimental Results

The results from VIPRE-W/MEFISTO-T, VIPRE-W/CPR and BISON/CPR simulations are compared against experimental data. The main focus of the validation is to determine the dryout prediction accuracy of both mechanistic and CPR methods. Dryout is predicted by MEFISTO-T when MFF=0 and by the CPR correlation when CPR=1. Dryout is measured during the tests by visual inspection of the temperature traces when the cladding temperature starts to increase significantly (often initiated at breakpoint). The results of the comparison are plotted in Figure 8 and Figure 9, "Min Dryout Margin" refers to MFF predicted by MEFISTO-T or CPR-1 predicted by the CPR calculations.

5.2.1. Prediction examples

In order to organize the analysis of the results, the experiments were divided in four different groups: Experiments with a “deep” dryout (high increase of measured temperature), with a “near” dryout (low increase of measured temperature), experiments with temperature instabilities (with different peaks of measured temperature), and non-dryout (with no increase of measured temperature). The results for deep dryout and near dryout are shown in Figure 8 while the results for temperature instabilities and non-dryout are shown in Figure 9. The estimated dryout occurrence is denoted by a red dot. The MEFISTO-T results using both “EPRI” and “DRFT” two-phase flow models (see Section 3.1) are presented.

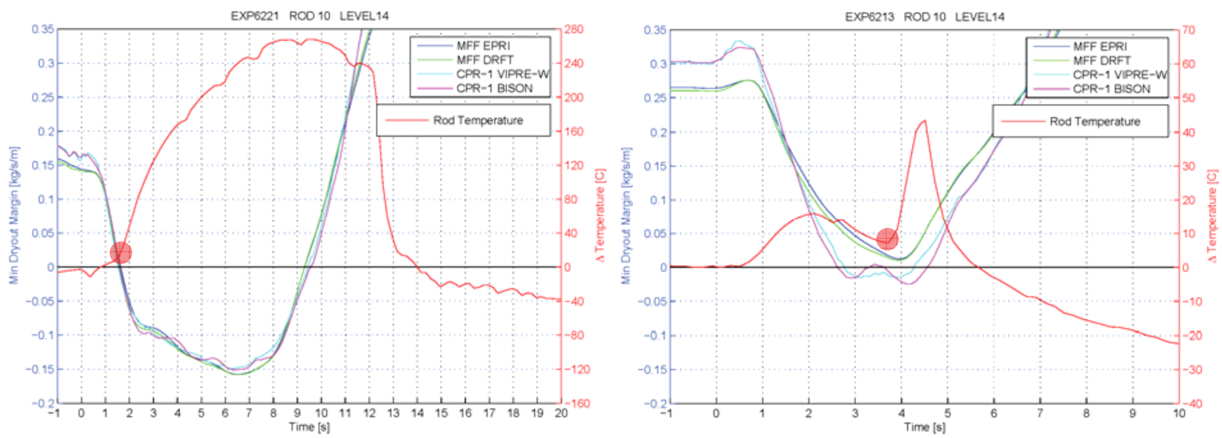


Figure 8. MFF, CPR-1 predictions and measured ΔT vs. time for EXP6221 and EXP6213

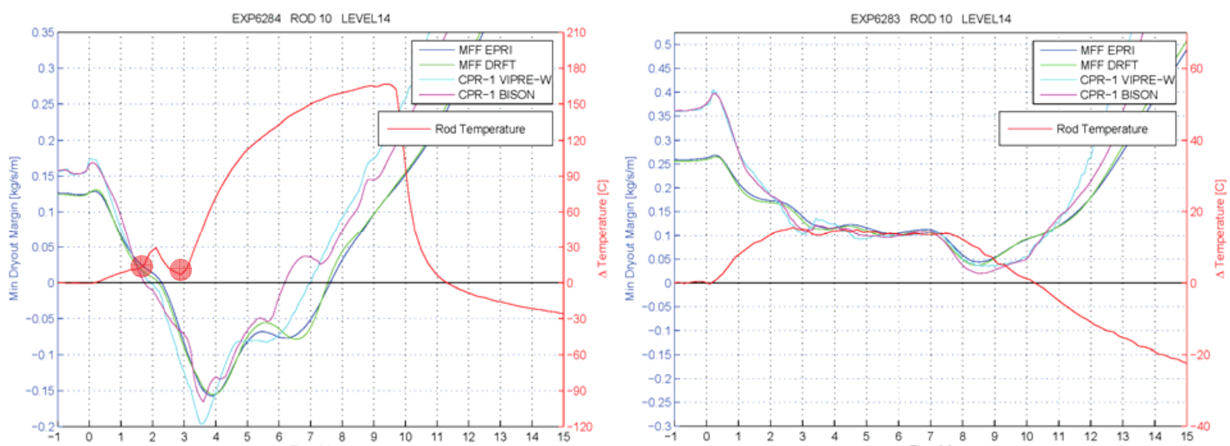


Figure 9. MFF, CPR-1 predictions and measured ΔT vs. time for EXP6284 and EXP6283

For experiments with a deep dryout (e.g. EXP6221), the code prediction agrees extremely well with the thermocouple measurements, for both MEFISTO-T and the CPR correlation. The predicted time to dryout is very similar to the measured time to dryout in all the cases. Most of the experiments of the project were of this type, and in all of them the codes showed a high prediction accuracy. However, it can be mentioned that these transients are so fast and so severe that it is relatively easy to correctly predict the correct time of dryout. It is however much more challenging for a simulation code to correctly predict a transient event when dryout was barely observed.

For experiments with a near dryout (e.g. EXP6213), the differences among codes become more appreciable, as expected. Dryout is not predicted by the MEFISTO-T simulations in some cases (although it predicts a very low value of minimum film thickness at this point) while it is predicted for the CPR correlations. In general, MEFISTO-T code results exhibit a best-estimate behavior while the CPR correlation was found to give slightly conservative predictions. EXP 6284 is one of the experiments with instabilities in the temperature measurements. In this kind of experiments, one or several peaks of temperature were found before the main dryout takes place. The wavy characteristics of the film thickness cause the film flow to disappear for some instants before rewetting takes place. In most of the cases, dryout was predicted in advance, especially for the CPR correlations. Finally, for the group of non-dryout experiments (EXP6283), all predictions were satisfactory since dryout was not predicted by any code.

In Figure 10, MEFISTO-T multi-film flow distributions for experiment number 6201 in all considered sub-channels at the most limiting time during the transient are plotted against the elevation. The sub-channels predicted in dryout are plotted using a red background while the other sub-channels are plotted using a blue background. The measured elevations of dryout are presented by yellow circles. It can be seen how dryout is predicted in several rods and elevations at the same time. In Figure 11, an overview of the dryout evolution predicted by MEFISTO-T can be seen. The film flowrate 3D distributions are color-mapped to the FIX-II bundle geometry considering different steps of times.

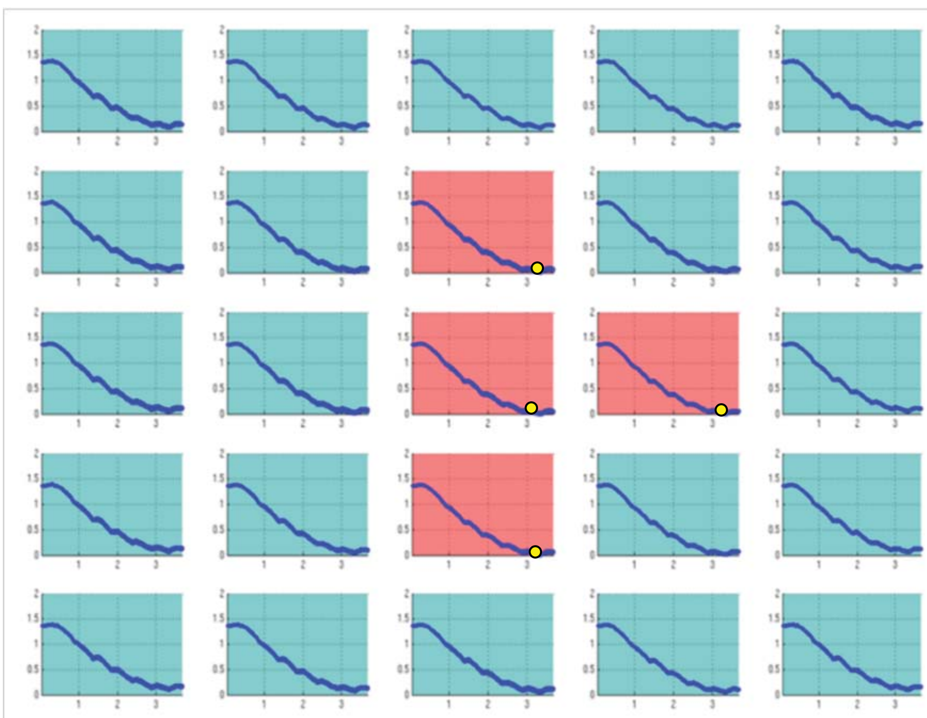


Figure 10. Axial film flowrate [kg/s/m] distributions in central sub-channels for EXP6201

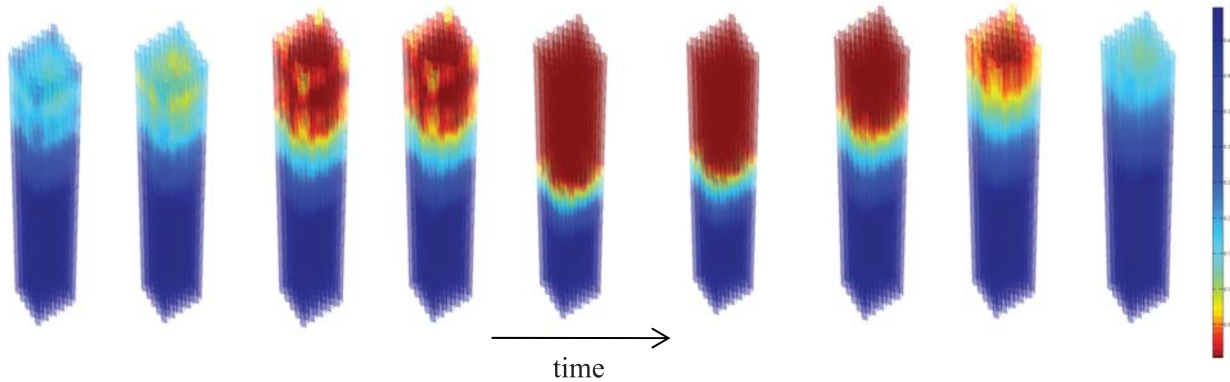
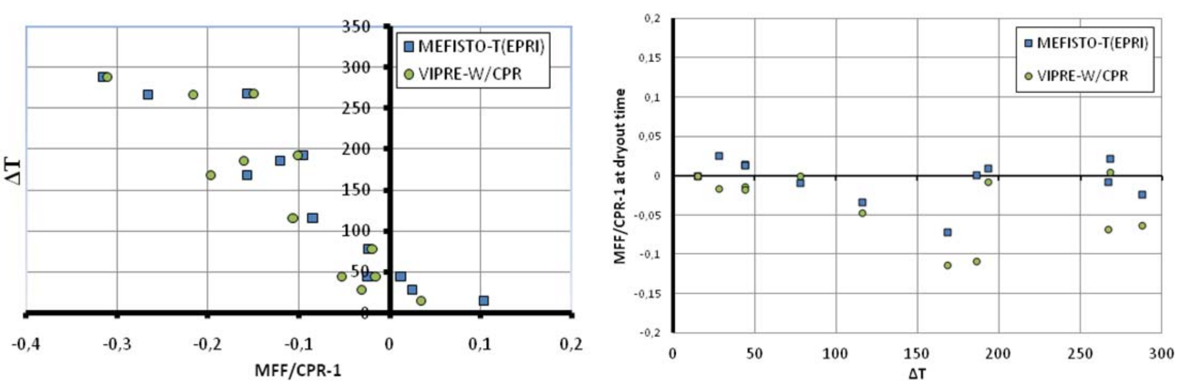


Figure 11. Film flowrate 3D distributions for different steps of time

5.2.2. Results and statistics

The relationship between increase of measured cladding temperature (ΔT) and MFF (or CPR-1) can be easily observed in Figure 12a. The points to the right of the Y axis represent the points for which the dryout has not been predicted. It can be seen how there is a clear relation between these parameters where lower predicted MFF and CPR corresponds to higher measured ΔT, as expected. This trend is more conservative for the CPR correlation results since it does not predict dryout in one experiment while MEFISTO-T does not predict dryout in three of them. In Figure 12b, the MFF (and CPR-1) at measured time to dryout are plotted versus ΔT (it must be noted that only the information for those tests with predicted dryout can be presented). Ideally, all points would lie on the MFF=CPR-1=0 line. It can be observed that the MEFISTO-T points lie on both sides and near the ideal line (the results of MFF at measured time to dryout lead to a mean of μ=-0.0053 kg/s/m and a standard deviation of σ=0.028 kg/s/m, corresponding to about -0.5 and 2.8% CPR error and standard deviation, respectively), typical of best-estimate predictions. The results from the CPR correlation are negatively biased, which demonstrate the conservative character of this method (the results of CPR-1 at measured time to dryout lead to a mean of μ=-0.041 and a standard deviation of σ=0.042).



a) **b)**

Figure 12. (a). Rod cladding temperature increase (ΔT) as function of MFF and CPR-1 (b). MFF and CPR-1 at time of measured dryout vs. rod cladding temperature

In general, the MEFISTO-T predictions are found to agree well with the experimental data, with few exceptions corresponding to the measured temperature instability cases, where the correct time of dryout is very challenging to predict.

5.2.3. Dryout front analysis

Within this project, the behavior of the liquid film in different rods and sub-channels at different steps of time was investigated in details. The transient temperature measurements along the rods were carefully examined in order to follow how fast the dryout front develops. In general when dryout occurs, a local dry patch first appears on the rod and then advances upstream and downstream along the rod. When the power decays and/or the mass flowrate increases, the liquid film begins to cover the rod again (rewetting), eventually reaching single-phase at the end of the transient. The results of these experimental observations were compared against MEFISTO-T simulations and the predictions were in good agreement. Note however that since MEFISTO-T does not have a model for post-dryout heat transfer, only the upstream dryout from predictions are relevant. The detailed results of this analysis are documented in [15].

6. CONCLUSIONS

In this project, several transient dryout prediction methods have been investigated: a mechanistic approach, using the MEFISTO-T code and an empirical approach (typical of BWR safety analysis) using a dryout correlation. The code prediction performances were compared against the FIX-II transient dryout experimental database. In comparison with other available transient dryout databases, the FIX-II tests include unique fast pressure increase transients, typical of BWR AOOs.

In order to reduce the execution time of the MEFISTO-T code, geometric simplifications of the sub-channel model capable to give reliable predictions were investigated. A model consisting of only two sub-channels was found to be the best compromise. It contains one sub-channel simulating the critical sub-channel and other channel simulating the rest of the fuel bundle. The results are nearly the same as for the detailed reference model with an execution time reduced by 20.

The code comparison with the experimental data shows that MEFISTO-T can provide a best-estimate prediction of the transient dryout tests, while the CPR correlation method yields a robust but slightly conservative CPR prediction.

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