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ANALYSES OF SINGLE-PHASE HEAT TRANSFER AND ONSET OF NUCLEATE BOILING IN A ROD BUNDLE WITH MIXING VANE GRIDS

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Abstract

In the framework of axial offset anomaly risk assessment in Pressurized Water Reactor (PWR) cores, an experimental program involving hydraulic and thermal-hydraulic tests on identical 5x5 bundle geometry was completed. It aimed at developing a consistent set of single-phase heat transfer model and associated onset of nucleate boiling (ONB) wall superheat criterion to further predict the existence and location of boiling zones in a PWR core, using a sub-channel Thermal-Hydraulic (T/H) code. This paper is devoted to the code-based analysis of the experimental data obtained on a bundle equipped with alternating simple support grids and mixing vane grids. Dedicated heat transfer models including a grid enhancement function are developed and the use of Frost & Dzakowic ONB wall superheat criterion is recommended along with these models.

1. Introduction

The impetus to improve cycle economy in Light Water Reactors has led to high duty core designs and considerable power up rates. However, a major associated concern in Pressurized Water Reactors (PWR) is the possible occurrence of Axial Offset Anomaly (AOA), which refers to a change in the core axial power distribution during operation. The cause of AOA is most likely crud buildup on fuel assemblies, in which boron compounds tend to concentrate. The crud deposition rate, and thus the precipitation rate of boron compounds, is temperature dependent and is strongly intensified by the presence of sub-cooled boiling. In the framework of AOA risk assessment in PWRs, the knowledge of boiling zones in the core is therefore crucial.

These boiling zones are predicted by sub-channel type Thermal-Hydraulic (T/H) core codes featured with an ONB criterion, which is typically a wall superheat criterion associated with a forced convective single-phase heat transfer correlation. But heat transfer correlations have not been validated against high fidelity rod-array experiments with respect to fuel assembly geometry and T/H conditions, as formerly pointed out in a comprehensive literature search [1] updated and summarized in [2]. Very briefly:

- (i) the widely used Dittus-Boelter correlation [3] originally developed for tubular automobile radiators in the 1930's agrees well with more recent correlations at PWR T/H conditions of interest.

However, its assessment against in-bundle heat transfer data or analytical developments, leads to contradictory insights, possibly resulting from (among others) the way the wall and bulk fluid temperatures were derived from the measurements;

- (ii) there is a lack of recent validation data for the Yao et al. correlation [4] which accounts for the axial evolution of the heat transfer in the wake of spacer grids;
- (iii) rod bundle experiments have been performed recently but they don't provide consistent heat transfer results for PWR-type fuel assembly bundles.

In an attempt to mitigate these concerns, a long term experimental program – NESTOR – was jointly set up in 2003 by CEA, EDF and EPRI, to reliably and accurately predict the existence and the localization of boiling zones in PWR cores with the aid of sub-channel type T/H core codes, and to further support the development of AOA risk assessment models. More specifically, the objective of this program was to provide high quality experimental data to (i) develop dedicated single-phase heat transfer correlations including a grid enhancement function, and (ii) assess an associated wall superheat threshold for ONB in PWR-type fuel assembly bundles.

The NESTOR program involved performance of tests on two 5x5 bundle configurations which respectively used (i) Simple Support Grids (SSG) only, designed to closely resemble a bare rod bundle (*SSG bundle configuration*), and (ii) alternating Mixing Vane Grids (MVG) and SSGs (*MVG bundle configuration*). The experimental program has been completed, and the present paper focuses on the code-based analyses of the results obtained on the *MVG bundle configuration*, as was previously done for the *SSG bundle configuration* [2]. After a general description of (i) the *MVG bundle configuration* tests and measurements, and (ii) the general features of the code-based analysis, this paper provides the main insights obtained with this experimental *MVG bundle configuration* data.

These analyses were concurrently carried out by the three NESTOR partners, each one running a different T/H code to check as to what extent the developed models were code-dependent. Specifically, the analyses were performed by CEA using FLICA-IV [6], EDF using THYC-COEUR [7], and the Pennsylvania State University (PSU) using VIPRE-I [8] on behalf of EPRI.

2. MVG bundle configuration tests and measurements

The NESTOR program consisted of two separate test loops – the unheated EDF-Chatou MANIVEL facility and the heated CEA-Grenoble OMEGA facility, each one housing the two afore-mentioned bundle configurations, in turn.

Figure 1 shows the bundle geometry as well as the sub-channel and heater rod nomenclature used throughout this paper. The span length in the bundles was roughly half that of industrial PWR bundle span length since intermediate grids (presently SSGs) had to be implemented to limit rod bow due to magnetic forces caused by electrical current in the OMEGA bundle heater rods. Also, except for the grid configuration, the geometry of the two bundles was the same.

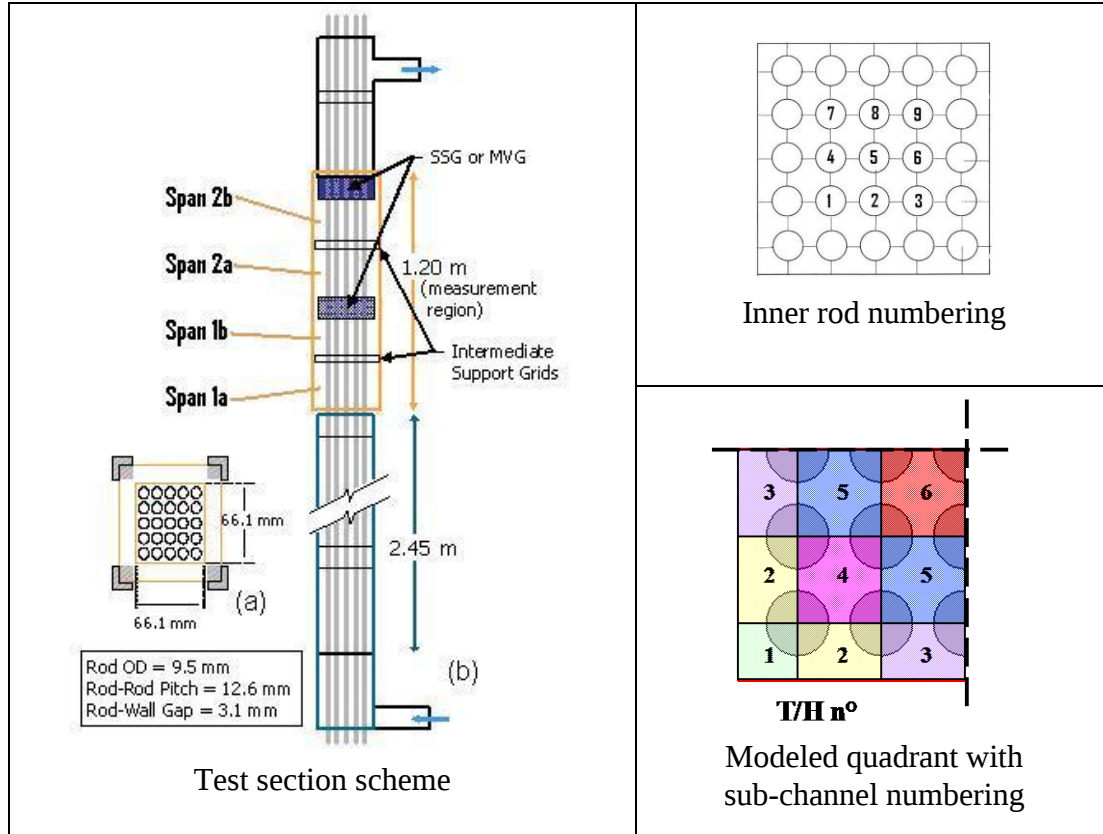


Figure 1 Rod bundle scheme, inner rod and T/H sub-channel numbering

Velocity and temperature measurements were made, respectively in MANIVEL and OMEGA loops over the upper 1.2 m of the bundle, as highlighted in Figure 1. Sections 2.1 and 2.2 discuss pertinent details of the measurements taken as well as the test conditions. Additional detailed information of the NESTOR experimental approach can be found in [5].

2.1 MANIVEL hydraulic tests and measurements

Local Laser Doppler Velocimetry (LDV) measurements were made in grid spans 1a to 2b (see Figure 1) at a test Reynolds number (Re) of approximately 100,000 (Re based on typical sub-channel hydraulic diameter). Local axial velocity measurements were taken over the 36 sub-channels of each bundle configuration at 18 different elevations. A total of 1,908 points (including 9 redundant points per sub-channel) were measured at each axial location. In addition, pressure drop measurements were taken during related tests respectively across two MVGs, one SSG, and along a bare section of the bundle; tests used for pressure drop measurements were performed at Re conditions between 35,000 and 140,000 to allow the development of a Re -dependent grid loss coefficient and friction loss correlation.

An error analysis resulted in uncertainty estimates better than $\pm 1.5\%$ on local velocity and $\pm 0.6\%$ on pressure drop measurements. The uncertainty estimate (including the positioning bias induced impact) on the quadrant-averaged velocity was better than $\pm 3\%$. Furthermore, consistency checks demonstrated acceptable test repeatability and measurement redundancy.

2.2 OMEGA T/H tests and measurements

Detailed inner rod surface temperature maps were collected during OMEGA tests using an array of sliding/rotating thermocouple probes. These measurements were taken in the inner 9 heater rods in axial increments of 30 mm and circumferential increments of 15°. Thermocouple measurements were additionally taken in sub-channel centers at the End of Heated Length (EOHL) during testing.

Primary OMEGA MVG tests included 13 single-phase tests and 14 ONB tests, with additional saturated boiling tests performed for estimating heater rod thickness variation. Single-phase test operating conditions were 15.5 MPa gauge pressure, 900 kW/m² inner rod heat flux (except one test performed at 600 kW/m²), and mass velocity ranging from 3,000 to 4,500 kg/m²/s; test average Reynolds numbers Re over the instrumented area roughly ranged from 300,000 to 620,000, and Prandtl numbers from 0.83 to 0.95. ONB tests included three series (with several runs at different inlet temperatures, each) at 15.5 MPa gauge pressure with “mass-flux/heat-flux” sets of [3,500 kg/m²/s; 900 kW/m²], [4,500 kg/m²/s; 900 kW/m²] and [3,500 kg/m²/s; 1,150 kW/m²], respectively.

Thermocouple calibration tests resulted in a ± 0.5 K measurement uncertainty (including a bias contribution of ± 0.3 K for the inner-wall temperature measurements). Uncertainty measurement in test inlet temperature, outlet pressure, mass flow-rate and heating power were 0.2 K, 0.1 MPa, 1 % and 0.1 %, respectively. Each test (which could last up to 8 hours) was performed under fairly stable boundary conditions (variations were lower than ± 0.2 K, 0.04 MPa, 0.8 % and 0.1 % for inlet temperature, outlet pressure, mass velocity and heating power, respectively), and heat balances for single-phase tests were very good.

3. General features of the code-based analyses

The code-based analyses were aimed at developing a consistent set of dedicated single-phase heat transfer model(s) and associated ONB wall superheat criterion to further predict the existence and localization of boiling zones in a PWR core using a sub-channel T/H code. They were conducted once the test data had been checked for their reliability and corrected for test condition variations. Additionally, since OMEGA temperature measurements were taken on the inner-surface of the heater rods, the needed outer-wall temperature distributions were determined using a 1D (radial) heat conduction calculation accounting for heater rod wall thickness variations (the latter were obtained by using the boiling tests specifically performed for this purpose).

It was necessary to obtain sub-channel averaged temperatures and velocities from T/H code simulations of the OMEGA tests since these parameters could not be measured directly in the OMEGA test section. Since the sub-channel codes don't capture the local grid effects on the flow (e.g. directed cross-flow mixing), the grid effects were instead represented on a macro-scale basis by using the pressure loss data from MANIVEL and simple turbulent mixing model coefficients that were calibrated to the NESTOR bundle configuration. The code-predicted results, therefore, behaved as if a 1/8th section symmetry existed in the test bundles, which was a limiting assumption for the *MVG bundle configuration*.

The NESTOR data analysis approach consisted of three successive stages:

(i) *T/H core code calibration*

Grid loss coefficients as well as bundle friction were determined from the MANIVEL test pressure drop measurements, whereas MANIVEL velocity and OMEGA EOHL fluid temperature measurements in single-phase tests were successively used for the turbulent viscosity and conductivity type parameter optimization, according to the process described in [2] for the *SSG bundle configuration*. However, for the *MVG bundle configuration*, a distinction between the SSG and MVG wakes was also considered, with the adoption in the SSG wake of the mixing model parameters optimized on the SSG configuration [2].

(ii) *Single-phase heat transfer test analysis*

Once the calibration in stage (i) was achieved, the T/H core codes were employed to compute sub-channel averaged coolant temperature and axial velocity (as well as pressure drops) along the OMEGA rod bundle for each single-phase test. With the combined use of OMEGA test outer-wall temperature and heat flux data, the *experimental* single-phase Heat Transfer Coefficients (HTC) were calculated, and an assessment of their axial and circumferential distributions was performed. This led to the development of dedicated single-phase heat transfer models including the grid effect.

(iii) *ONB test analysis*

For each ONB test, this analysis included the determination and use of:

- the *experimental* ONB location within the instrumented area by a thorough visual inspection of the axial variation in outer-wall temperature data within the single-phase heat transfer region (pre-ONB) and two-phase boiling region (post-ONB),
- the associated *experimental* and *computed* ONB wall superheats based on the *experimental* and *computed* outer-wall temperature, respectively, as well as the *computed* pressure for the saturation temperature. *Computed* outer-wall temperature and pressure were provided by a simulation of the test (as performed in stage (ii)), using the afore-developed dedicated heat transfer models.

The three partner core codes were concurrently run and provided similar general insights. These insights are presented below for the three successive analysis stages described above.

4. Pre-calibration of T/H core codes

This stage of the analysis has shown that:

- (i) the bundle friction coefficients obtained from MANIVEL pressure drop measurements are 10 % lower than Colburn correlation ones;
- (ii) different sets of T/H code input parameters (e.g. those from friction and grid loss coefficients, and turbulent mixing coefficients) led to consistent *computed* sub-channel velocities. But they differed significantly from the *experimental* values, mostly in the MVG wake as anticipated due to the afore-mentioned modeling limitations; this is underlined in related Figure 2 which compares *computed* and MANIVEL *experimental* axial velocity profiles in the MVG and SSG wakes for sub-channel types 5 and 6;

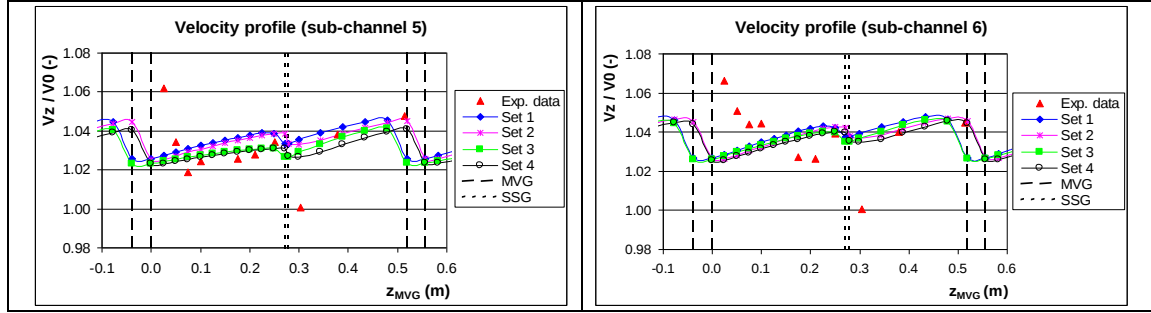


Figure 2 Axial profile of normalized experimental and computed velocities

- (iii) an optimized value for the turbulent conductivity type parameter could not be obtained on the *MVG bundle configuration*, either with or without a distinction between the SSG and the MVG wakes. This remains as an unexplained concern. Further, it was observed that the *computed* and *experimental* EOHL fluid temperature maps during the optimization process exhibited very different patterns (see Figure 3).

For further analyses of the OMEGA tests, a “*best-estimate*” physical value was adopted in each code for the turbulent conductivity type parameter in the MVG wake, and associated bounding bias bands were estimated for the computed temperatures (typically, ± 1.2 K for central sub-channel type 6).

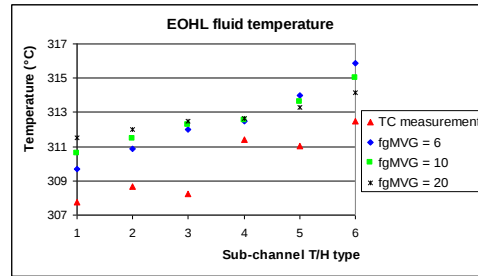


Figure 3 Cross-section distribution of EOHL fluid temperature

5. Heat transfer analysis of single-phase tests

The heat transfer analysis of the single-phase tests was based on the *experimental* local HTC h_{exp} determined at each inner-wall temperature measurement location, using the corresponding local outer-wall temperature T_{wo} and heat flux ϕ_{wo} , and adjacent sub-channel-averaged fluid temperature T_f provided by the associated T/H core code simulations. T/H code simulations also provided sub-channel Reynolds and Prandtl numbers along with associated H_{DB} Dittus-Boelter-predicted coefficient. This allowed for further comparison with *experimental* HTC (via R_{DB} ratio h_{exp}/H_{DB}) and modification to the Dittus-Boelter correlation with respect to the Reynolds number dependence as well as development of a grid enhancement function.

Note that these *experimental* HTCs were subjected to a large uncertainty range, depending on their value. Over the whole NESTOR MVG single-phase database, these uncertainties roughly varied from 10 % to 35 %. Additionally, the temperature distributions observed for the reference test performed thrice highlighted that the repeatability reduced with time in a given test and, to a

lesser extent, with elevation. These distortions resulted in up to 7 % HTC reduction between the beginning and the end of the test series performance (no longer considering the very last test performed 2 months later the previous one). No actually supported root-cause was found.

This analysis of the single-phase flow tests showed that:

- (i) irrespective of the heated rod, MVGs resulted in a large heat transfer enhancement with a large circumferential scatter, both decreasing with the distance to the upstream MVG., Fully-developed flow condition was not reached in the MVG wake (see Figure 4, LHS). Indeed, the heat transfer in the intermediate SSG wake is significantly higher than that in the previous SSG configuration with SSGs only [2];
- (ii) the 2-D distributions of the as-determined *local* HTC (h_{exp}) over each instrumented heater rod demonstrated a complex pattern, specially for the non-central heater rods, which are surrounded by different sub-channel types. Over the central rod, the circumferential distributions tend to have a general sinusoidal shape with a 180° and 90° period in the MVG and SSG wakes, respectively (Figure 5), but this shape deteriorated with the distance Zg to the upstream grid. Furthermore, the associated axial distributions strongly depend on the circumferential locations, according to an unclear relationship (Figure 4, RHS).

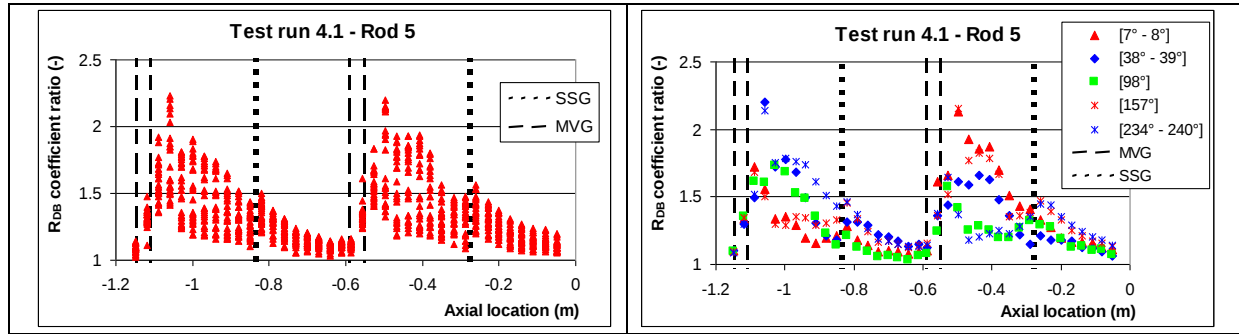


Figure 4 Axial distribution of local experimental HTC R_{DB} ratio (i) over the whole circumference (LHS), and (ii) for a few angular locations (RHS)

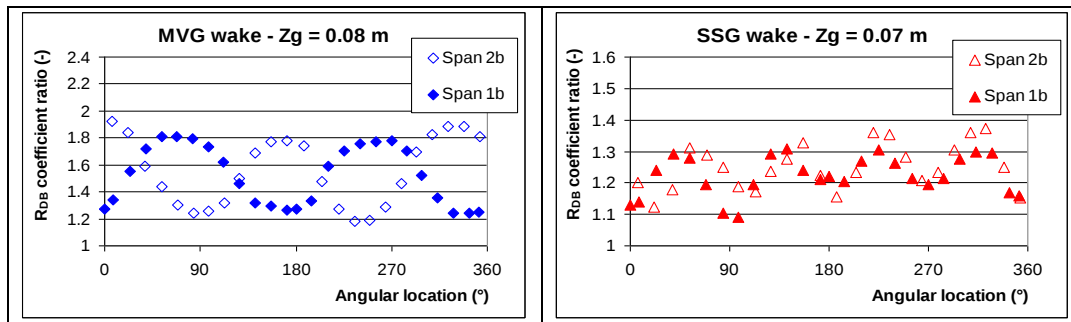


Figure 5 Local experimental HTC R_{DB} ratio as a function of angular location and grid span, in (i) the MVG wake (LHS) and (ii) the SSG wake (RHS)

Nevertheless, consistent with NESTOR project aim and methodology, dedicated single-phase heat transfer models were developed for the *minimal*, *maximal* and *circumference-averaged* HTC per elevation over the central rod only (n° 5 in Figure 1) for the MVG and SSG wakes

data, separately. They were based on the following features demonstrated by the central rod HTC, irrespective of the grid wake:

- (i) good axial repeatability between grid spans 1 and 2, and dependence on the distance Z_g to the upstream grid that can be approximated by a decreasing exponential function f_g except in the close downstream vicinity of the MVGs (Figure 6);
- (ii) heat transfer dependence on sub-channel-averaged Reynolds number different from Dittus-Boelter one. An exponent of 0.94 to 1.00 - dependent on the T/H code used - had to be adopted instead of 0.8. Note that an exponent of 0.85 exponent was suggested with the SSG bundle test data [2]. This additionally supported the fact that fully-developed flow was not achieved along the MVG wake. For each code used, two different (but close) values could be adopted for the MVG and SSG wakes, respectively, independent of the defined HTC, or a single mean value.

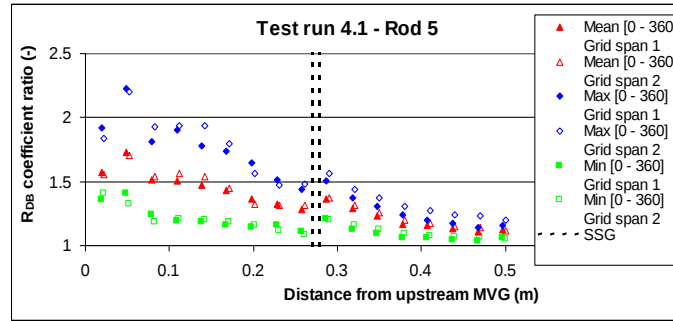


Figure 6 Maximal, minimal and circumference-averaged HTC R_{DB} ratio over Rod 5 as a function of distance from upstream MVG and grid span

These different dedicated single-phase heat transfer models (one per coefficient type, grid wake type and T/H core code used) have therefore the following form

$$h_c = H_{DB} \cdot Re^a \cdot f_g$$

where (i) a ranges between 0.14 and 1.00, and (ii) $f_g = b \cdot e^{c Z_g}$, with specific constants b and c . A Yao type formulation [4] could not be adopted since fully-developed flow was not achieved along the grid wakes. Each T/H code equipped with its dedicated heat transfer models roughly represented the *experimental* data within $\pm 10\%$ (HTC) and ± 2 K (outer-wall temperature), as illustrated in Figure 7 for the maximal heat transfer along the MVG wake.

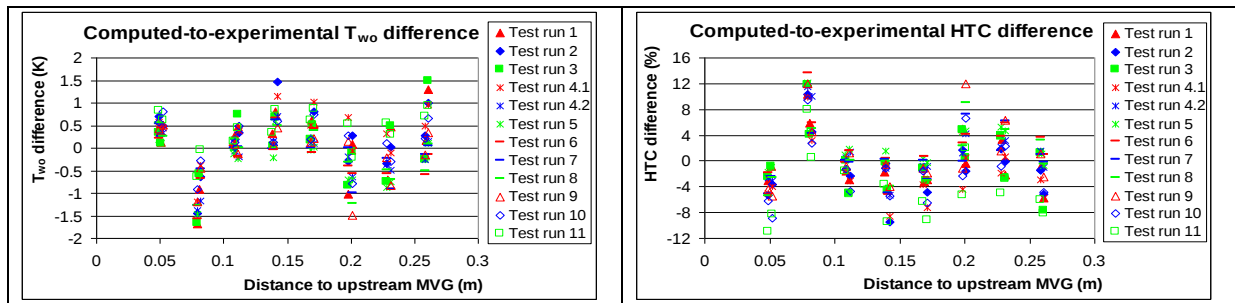


Figure 7 Computed-to-experimental outer-wall temperature differences (LHS) and HTC differences (RHS) as a function of distance to upstream grid

6. ONB test analysis

Consistent with the single-phase test analysis and related dedicated heat transfer models, the analysis of the ONB tests was devoted to the “*first upstream*” and “*last downstream*” local ONB locations in each grid span as well as the “*averaged*” ONB location (using the circumference-averaged outer-wall temperature profile). The analysis performed on the central rod confirmed:

- (i) the local nature of ONB phenomenon which axially propagates downstream around the rod. The action of the grids (especially MVGs) may result in a downstream recovery of the single-phase flow either over the rod circumference or over an angular sector only, depending of upstream flow conditions (Figure 8);
- (ii) it is difficult to accurately locate the *experimental* ONB boundary despite a careful visual inspection of the outer-wall temperature profiles (Figure 9). Thus, an analysis of the *calculated-to-experimental* ratio of the outer-wall temperatures further demonstrated that previous anticipated *experimental* ONB locations were obviously wrong or questionable.

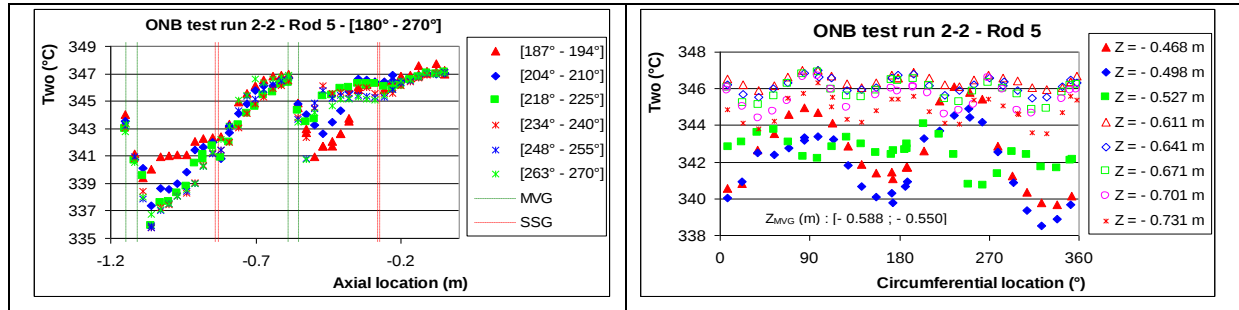


Figure 8 Axial profile (LHS) and circumferential distribution (RHS) of local outer-wall temperature over Rod 5 as a function of circumferential location and elevation Z

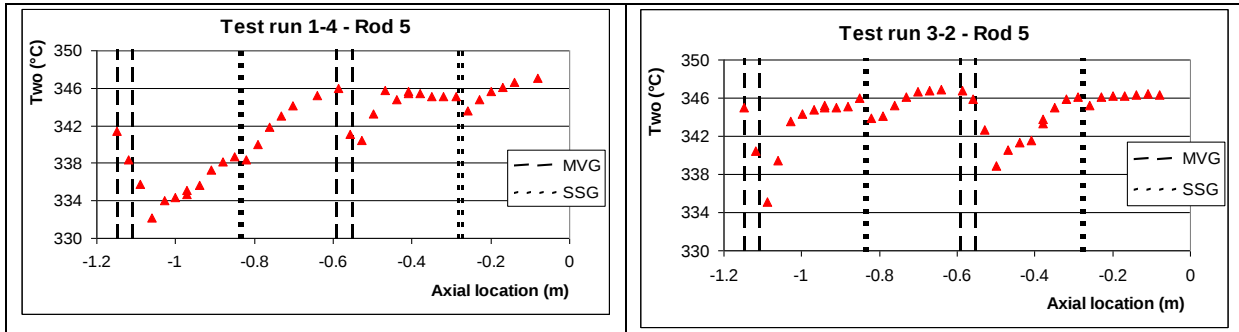


Figure 9 Illustrative axial profiles of local outer-wall temperature

For the most reliable *experimental* ONB locations:

- (i) the *experimental* ONB wall superheats were consistent with those predicted by the correlations in [9] [10], irrespective of ONB considerations type and location in MVG or SSG wake. They ranged between 0.5 K and 1.4 K (Figure 10), despite the uncertainty in ONB location and wall temperature, whereas the correlations provided values close to 1 K;

- (ii) the *calculated* ONB wall superheats associated with the *experimental* ONB locations using the dedicated single-phase heat transfer models demonstrated a large scatter and differences with corresponding *experimental* values, depending on ONB location and test run conditions (Figure 10). These features largely resulted from the performance/accuracy of the single-phase heat transfer models that were developed and used.

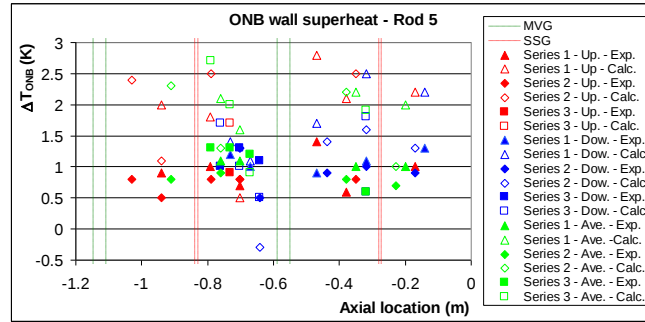


Figure 10 Experimental and Calculated ONB wall superheat at the experimental locations as a function of elevation, ONB type (Upstream, Downstream and Averaged) and ONB test

Considering the observations regarding *experimental* ONB wall superheats, it is recommended to adopt Frost & Dzakowic ONB wall superheat criterion [10], and allow for a ± 2 K uncertainty in calculated outer-wall temperatures provided by the dedicated HTC models to further calculate the ONB locations based on both *best estimate* values and related in NESTOR MVG bundle type configurations.

This approach provided a good agreement between NESTOR *experimental* and *calculated* ONB locations; indeed, Figure 11, LHS shows the related ONB location differences are less than 6 cm (absolute values). However, it would result in a large uncertainty (roughly ± 0.15 m range) on the calculated ONB locations in a PWR core loaded with the same MVG fuel assembly design; Figure 11 (RHS) visualizes the related uncertainty ranges on both the *first upstream*, *averaged* and *last upstream* locations, for a schematic core at a 600 kW/m^2 heat flux and a 500,000 Reynolds number, considering the afore-defined MVG enhancement function applies all along an actual industrial grid span.

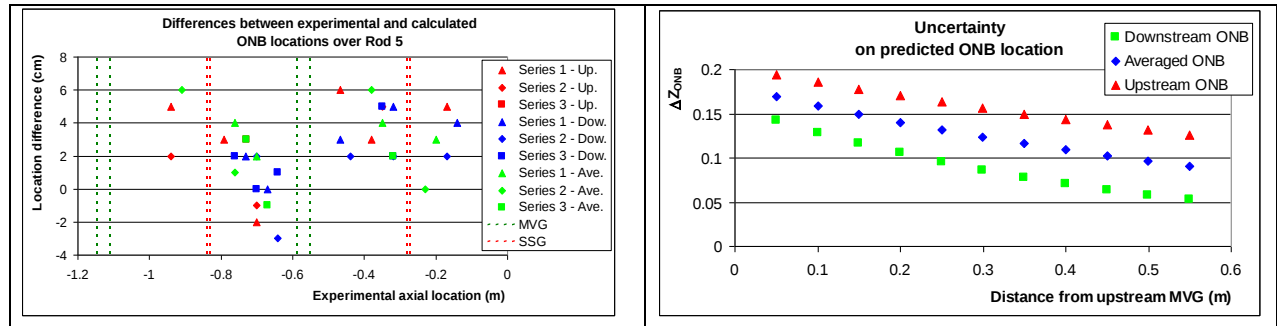


Figure 11 Experimental-to-best estimate calculated ONB location differences (LHS) and impact of 2 K uncertainty in outer-wall temperatures on predicted ONB location in a schematic PWR core (RHS)

7. Conclusion

The NESTOR program was a collaborative effort between CEA, EDF, and EPRI with the aim of developing an accurate ONB prediction model for PWR fuel bundles based on a wall superheat criterion associated to dedicated single-phase heat transfer model(s) for PWR bundles. It involved:

- (i) a series of unheated and heated tests on two successive 5x5 rod bundle configurations utilizing both SSG- and MVG-type spacers, with local LDV axial velocity field characterization and thermocouple measurements to generate 2-D rod surface temperature maps. To date, all tests have been completed;
- (ii) a code-based analysis of the test data with three different T/H core codes to provide the required sub-channel averaged fluid temperature and velocity. After a pre-calibration of these codes with respect to the bundle geometrical configuration; single-phase and ONB tests were analyzed in turn.

This paper summarizes the code-based analysis of test data obtained on a bundle using alternating mixing vane grids (MVG) and simple SSGs. Similar insights were obtained with the three core codes. They are as follows:

- (i) Although successful calibration of the flow dynamics related parameters was achieved, the *experimental* and *computed* distributions of axial velocity displayed different patterns. The same applied for the fluid temperature at the EOHL, and an optimised value could not be achieved for the turbulent conductivity type parameter.
- (ii) Dedicated single-phase heat transfer models were developed, separately for MVG and SSG wakes. Related *maximal*, *minimal* and *circumference-averaged* HTC per axial location, had the characteristics of a modified form of the Dittus-Boelter correlation, with a Reynolds number exponent ranging between 0.94 to 1.00, depending on the code used and grid wake, instead of 0.8, and a decreasing exponential type functional dependency along the grid wake. These models depend on the code used and grid wake type, but they all roughly represented the *experimental* HTCs within $\pm 10\%$ and wall temperature within ± 2 K.
- (iii) *Experimental* ONB wall superheats were consistent with classical correlations, and the adoption of Frost & Dzakowic correlation along with the developed HTC models is recommended to further locate the ONB in similar bundle configurations; the resulting differences (absolute values) between the *experimental* and *computed* ONB location were less than 6 cm.

For the application of this ONB location predictive method from NESTOR tests to a PWR core loaded with the same MVG design fuel assembly, a ± 2 K uncertainty in computed outer-wall temperature should be applied. The related impact on ONB location would roughly be in a ± 0.15 m range.

7. References

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