Extension to Heavy Liquid Metal coolants of the validation database of the ANTEO+ sub-channel code

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Abstract. Among the numerous numerical methods available for preliminary design verification purposes, the sub-channel one has historically been the reference, thanks to its ability to cover the scale between CFD and system codes, which is the one of particular interest for the core designer. Recently, the sub-channel code for liquid metal applications ANTEO+ has been developed by ENEA and a comprehensive validation performed, covering all the salient aspects of the fuel assembly thermal-hydraulic analysis like pressure drops, sub-channel and outer clad temperatures. Due to the database available at the time, the focus for the sub-channel temperatures validation was mainly related to sodium and sodium eutectics coolants. Thanks to the increasing interest in heavy liquid metal coolants for fast reactor applications, numerous experimental activities have been very recently performed (KYLIN-II, KALLA, CIRCE) and many are still ongoing, enabling the extension of the previous ANTEO+ validation database so to make this tool even more persuasive for Generation IV reactor concepts applications and mostly to estimate the uncertainty to recon to the code results. In the present work, ANTEO+ validation against the most recent experiments with heavy liquid metal coolant is presented: several tens of new experimental points have been considered in this work, covering a broad range of configurations, which spans over the one of anticipated interest. The results of this validation activity have confirmed the good predictive ability of the code, notably when compared to other state of the art tools. Some criticalities have also emerged, especially to what concerns the sub-channels and pins close to the wrapper, which significantly modifies their thermal field; this has a particular impact on the Nusselt number, highlighting the lack, in the open literature, of a reliable correlation for the outer row of pins.

Key Words: Validation, heavy liquid metal, sub-channel, Generation IV.

1. Introduction

Generation IV concepts are acquiring considerable momentum in the fast reactor community because of the enhanced sustainability and safety performances they are inspired to; particularly, interest is gravitating around Liquid Metal Cooled (LMC) designs mainly for their favorable neutronic and thermal-hydraulic (TH) characteristics [1-2]. To fulfill completely the Generation IV objectives, it is necessary to embed – among the others – safety related considerations at the design phase; this means evaluating TH conditions at the beginning of the aforementioned phase. For this task, among the numerous numerical methods available for preliminary design verification purposes, the sub-channel (*FIG. 1*) one has historically been the reference, thanks to its ability to cover the scale between CFD and system codes, which is the one of particular interest for the core designer.

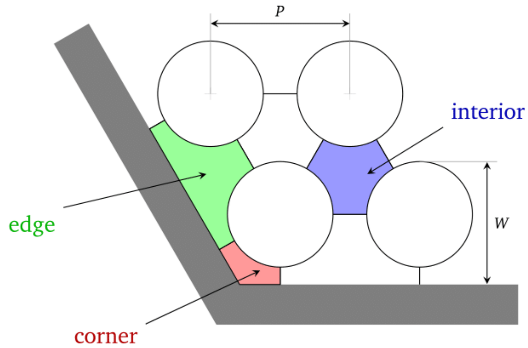

FIG. 1. Sub-channel definition for rods in a triangular lattice.

For this reason, ENEA recently developed the sub-channel (SC) code for LMC applications ANTEO+ [3]. In a designer’s perspective, to assess the uncertainty of the code results, a comprehensive validation activity, in a variety of geometric configurations and operative conditions, has been performed, covering all the salient aspects of the fuel assembly thermal-hydraulic analysis like pressure drops, flow split, SC and outer clad temperatures. Due to the database available at the time, the focus for the SC and clad temperatures validation was mainly related to sodium and sodium eutectics coolants.

Thanks to the increasing interest in heavy liquid metal coolants (HLMCs) for fast reactor applications and to the numerous industrial projects started in the latest years, various experimental activities have been very recently performed (e.g. KYLIN-II [4], KALLA [5], CIRCE [6]) and many are still ongoing. These experimental efforts enable the extension of the previous ANTEO+ validation database – on SC and clad temperatures – to make this tool even more persuasive for Generation IV reactor concepts applications. Due to the different physical properties and thermal behaviour between sodium and HLMCs, indeed, validation results for the former cannot be directly transferred to the latter, and a dedicated validation must be performed to assess ANTEO+ accuracy when applied to HLM-cooled bundles.

In the present work, therefore, the ANTEO+ validation against the most recent experiments with HLMCs is presented, starting with a brief description of ANTEO+ and the previous validation campaign main results, followed by the comparison of the code predictions with experimental data for the setups described in [4], [5] and [6]. Finally, the obtained results are discussed and conclusions drawn.

2. ANTEO+

ANTEO+ was developed by ENEA with the main objective of simplifying the problem description without penalizing accuracy thus enabling a more transparent interface with the user – necessary in a rationale design process – and, at the same time, considerably speeding up the calculation. For achieving this double task, at first the various terms of the governing equations have been analysed, identifying those that do not contribute significantly to the particular problem. Deciding to discard a specific phenomenon, however, would have restricted the validity range of the code, so the field of application had to be clearly identified and decided beforehand; then, a set of equations, models and approximations coherently set up [3]. For ANTEO+ the steady state, single phase, forced convection regime was selected being the one usually of interest in the preliminary design phase of a power reactor.

Following the aforementioned procedure resulted in a final set of equations remarkably different from the one usually solved by COBRA-like codes [7], being more simple and avoiding to solve the transverse momentum equation, thus avoiding convergence problems with the possibility of maximizing modelling efficiency for the selected validity range [3].

Summarizing, the modelling adopted in ANTEO+ corresponds to a system of SCs dynamically connected only at the inlet and energetically connected throughout the whole simulated length.

2.1.Previous validation campaign

Since SC codes rely mainly on empirical correlations, the validation phase is of paramount importance for establishing the degree of confidence in the results. For this reason, a thorough validation has been performed encompassing all the main models in a wide range of operating conditions and geometric configurations of interest; during the validation, it was also possible to crosscheck that the anticipated and actual validity domains coincide, thus confirming the correctness of the derived set of equations and approximations.

The main results of the validation, covering flow split parameters (X), bundle pressure drop (ΔP), SC temperatures (ΔT_{norm}) and outer clad-coolant bulk temperature differences ($\Delta T_{clad-cool}$), are reported in Table I where

$$\Delta T_{norm} = \frac{T - T_{in}}{T_{out} - T_{in}} \quad , \tag{1}$$

being T the SC temperature at some axial elevation, T_{in} and T_{out} the inlet and average outlet temperatures respectively[1]. The validation is here summarized by the average relative error, defined as

$$\bar{\varepsilon}_{rel} = \frac{1}{N}\sum_{i=1}^{N}\frac{|x_{exp} - x_{calc}|}{x_{exp}} \quad , \tag{2}$$

where x_{exp} and x_{calc} are the physical parameter under study as given by the experiment and the calculation respectively, and the 90% confidence interval indicating that 90% of the points have an error $\bar{\varepsilon}_{rel}$ less than the reported value.

One of the limits of the validation database used at the time was the lack of specific data for HLMC. While for dynamic processes, like flow split and pressure drop, results for water and sodium are easily transferable to HLM [8], for thermal and energy related phenomena, like SC and clad temperatures, it must be demonstrated – via validation – that ANTEO+ accuracy is still in line with the one reported in Table I. In the following, therefore, the database for ΔT_{norm} and $\Delta T_{clad-cool}$ will be extended to HLMC including the most recent data available from literature.

TABLE I: Main results from the ANTEO+ validation campaign [3].

	$\bar{\varepsilon}_{rel}$ **[%]**	**90% confidence interval [%]**
$\boldsymbol{X}$	4.8[2]	11.4
$\boldsymbol{\Delta P}$	3.3	5.8
$\boldsymbol{\Delta T_{norm}}$	3.9	8.6
$\boldsymbol{\Delta T_{clad-cool}}$	7.0	12.5

[1] ΔT_{norm} essentially represents the ratio of the local SC temperature increase to the average bundle temperature increase at the outlet section.

[2] The error on the flow split parameters goes down to 1.8% in the case of turbulent flow, the one usually of interest for design applications of LMC.

TABLE II: Collection of experiments used for SC and clad temperature validation. Main physical and geometrical parameters are also given.

Ref.	Coolant	N_{pin}	P/D	H/D	Pe
Spacer: Wire					
KALLA	Lead-bismuth	19	1.279	40	1075
KYLIN-II	Lead-bismuth	61	1.116	25	1050
Spacer: Grid					
CIRCE	Lead-bismuth	37	1.800	-	2400

3. Validation extension to HLMs

Recent data from the experimental facilities of KYLIN-II [4], KALLA [5] and CIRCE [6] falling inside the validity range of ANTEO+ have been used; a summary of the main parameters of each bundle – like the number of pins N_{pin}, the pitch-to-diameter ratio P/D and the wire lead pitch-to-diameter ratio H/D – used in the validation is reported in Table II. It is to be noted that the coolant is, in all the cases, the lead-bismuth eutectic (LBE)[3] and so, no pure lead experimental data are available; this is not of particular concern relatively to the SC and clad temperatures due to the similar values and behaviour of the physical parameters of interest (Prandtl's number for example), especially in forced convection. The following validation can thus be directly transferred to lead with a high degree of confidence.

3.1. KALLA

An experimental campaign on a 19-pin electrically heated hexagonal bundle with wire spacers cooled by LBE was conducted at the Karlsruhe Liquid Metal Laboratory (KALLA) [5] in the frame of the European research project Safe Exploitation Related Chemistry for HLM Reactors (SEARCH). The geometry and operating conditions were chosen so to be representative of the MYRRHA [9] fuel assembly.

Results for a case with an axially and radially uniform power profile are reported in *FIG.2*. The clad temperature in *FIG.2* is the average outer clad temperature of the corresponding pin. Results are also summarized in Table III. In *FIG.2* and Table III, the nomenclature is the following:

- "Mikityuk+Zhukov" indicates that the Nusselt's number has been calculated by means of the Mikityuk's correlation [10] for the central pins and the Russian correlation [11] for the edge and corner pins; the Russian correlation was built *ad-hoc* for these types of pins.
- "Mikityuk" indicates that the Nusselt's number, for all the pins, has been calculated by means of [10].

[3] ANTEO+ structure and models are identical to the ones presented in [3]. For LBE, the materials property set reported in [3] has been used.

- "Ma" indicates that the Nusselt's number, for all the pins, has been calculated based on [3].

ANTEO+ calculations in *FIG.2* – and also for all the other cases in this validation work – has been performed using, for the flow split and energy mixing, the correlation from [12] that was proven to be the most reliable in the previous validation campaign.

TABLE III: Comparison summary between simulations and KALLA experimental data.

		$\bar{\varepsilon}_{rel}$ [%]
ΔT_{norm}		11.9
$T_{clad} - T_{in}$	Mikityuk+Zhukov	2.6
	Mikityuk	3.4
	Ma	3.4

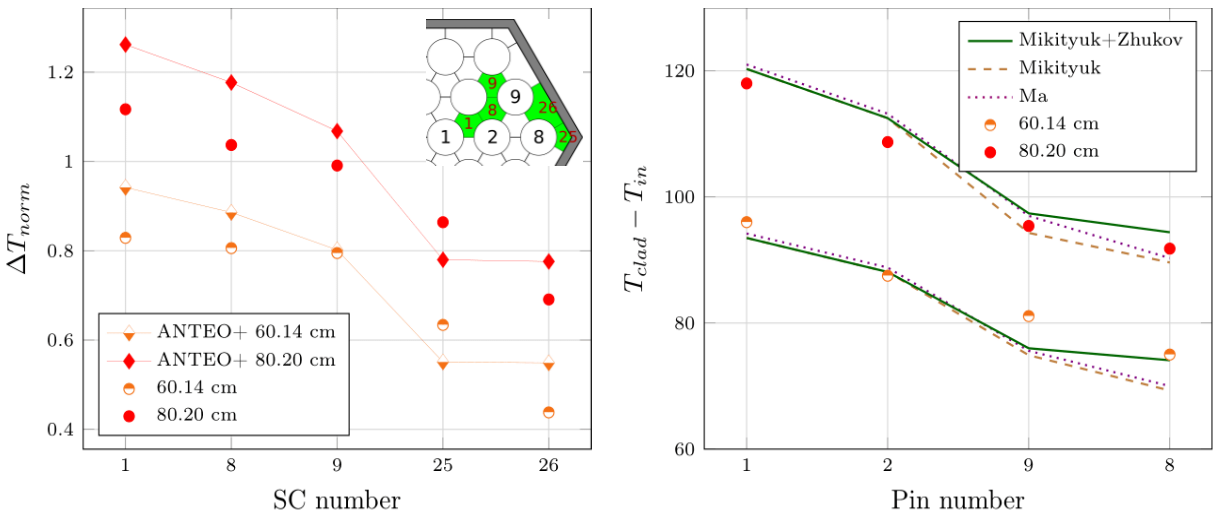

FIG. 2. Comparison of KALLA experimental data for the SC temperature distribution (left) and the outer clad temperature (right) at two axial elevations from the beginning of the heated section.

3.2.KYLIN-II

In the frame of the ADS research project launched by the Chinese Academy of Sciences (CAS), the Institute of Nuclear Energy and Safety Technology (INEST) undertook the design of a reactor cooled by LBE named CLEAR-I [13]. To support CLEAR-I design, the KYLIN-II [4] multi-functional facility including material, thermal-hydraulic and safety loops has been established; a test section composed of 61 electrically heated pins arranged in a hexagonal bundle with wire spacers has also been installed and operated.

The forced convection case from [4], with an axially and radially uniform power profile, has been used for the validation; results are reported in *FIG.3* and Table IV. Because the clad temperature data refers to a central pin the only available correlations are "Mikityuk" and "Ma"; in *FIG.3* results are reported only for the "Mikityuk" case being "Ma" results basically overlapping.

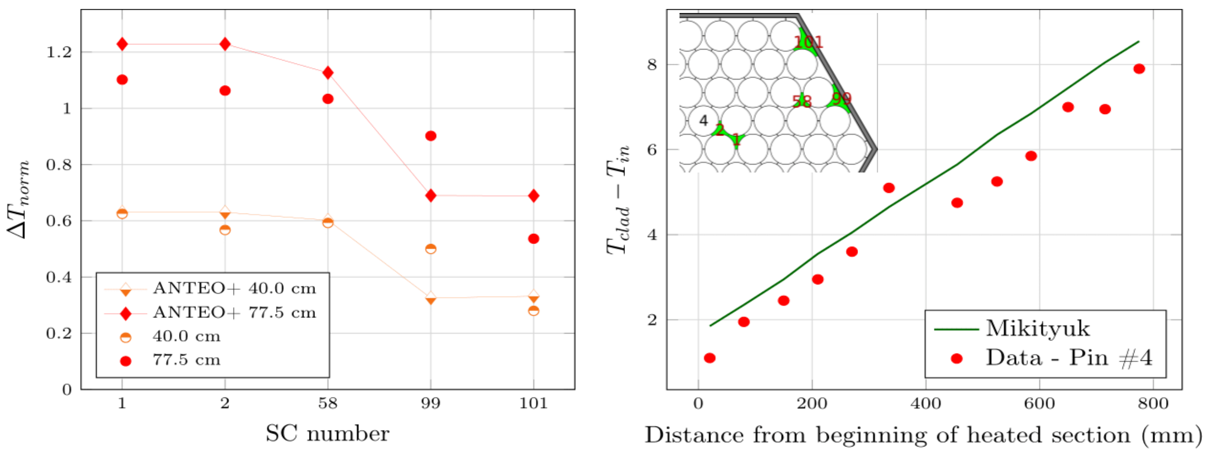

FIG. 3. Comparison of KYLIN-II experimental data for the SC temperature distribution at two axial elevations from the beginning of the heated section (left) and the outer clad temperature (right).

TABLE IV: Comparison summary between simulations and KYLIN-II experimental data.

		$\bar{\varepsilon}_{rel}$ [%]
ΔT_{norm}		15.5
$T_{clad} - T_{in}$	Mikityuk	19.9
	Ma	17.8

3.3. CIRCE

Within the 6th EU Framework Program, ENEA assumed the commitment to perform an integral experiment aimed at simulating the primary flow path of an HLM cooled – pool-type – nuclear reactor, implementing a new experimental activity named Integral Circulation Experiment (ICE) to be performed in the CIRCE facility [6]. The ICE test section includes an assembly of 37 pins, spaced by grids, arranged in a hexagonal bundle.

Among the numerous transient tests, a forced convection steady state run was also performed featuring an axially and radially constant power profile. Results for the clad outer temperature obtained with the "Mikityuk" correlation are reported in *FIG.4*; the error bars stem from the declared ±15% uncertainty on the heat flux due to the use of bifilar-type pin rods [6] and so they do not take into account the other sources of uncertainty – like flow and power oscillations. The clad temperatures in *FIG.4* are measured and evaluated at the location marked by the blue bar. A summary of the results is also reported in Table V.

TABLE V: Comparison summary between simulations and CIRCE experimental data.

		$\bar{\varepsilon}_{rel}$ [%]
$T_{clad} - T_{in}$[4]	Mikityuk	5.9
	Ma	6.5

[4] The correlation for the Nusselt's number reported in [11] is not used for the ICE test section because the P/D is out of the range of the correlation.

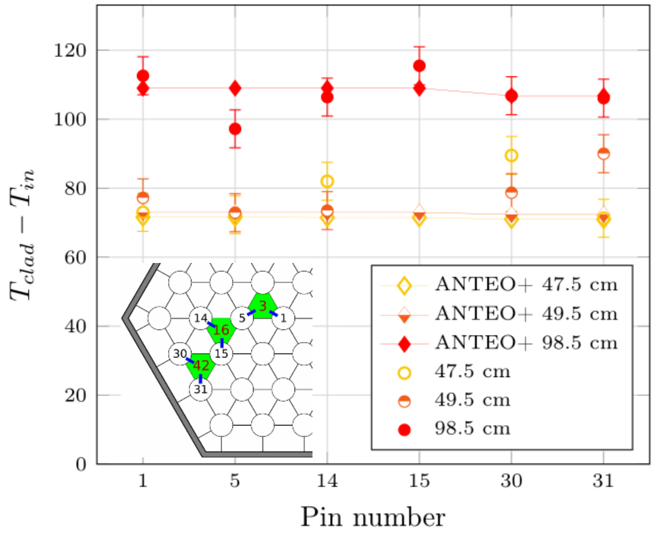

FIG. 4. Comparison of CIRCE experimental data for the outer clad temperature at three axial elevations from the beginning of the heated section. The temperature was measured at the location mark by the blue bar.

3.4.Validation Overview

A graphical summary of the validation is reported in *FIG.5* (where clad temperature results are relative to the "Mikityuk" correlation), while a quantitative one in Table VI.

4. Discussion

For each experiment analyzed, there are a number of considerations that can be done to better understand the results and the value of the overall validation work.

4.1.KALLA

For what concerns the SC temperature distribution it can be noted (*FIG.2*) that ANTEO+ overpredicts the temperature for the interior SCs while, for the edge and corner ones, overestimates mixing. In the simulations, indeed, the edge and corner SCs have the same temperature while the data show that the corner one is colder.

An important consideration must however be made: the difference between the SC center temperature (where the thermocouple is located) and the clad temperature oscillates between 10°C and 25°C which must be compared with a SC temperature increase around 100°C – for the hottest SC at the location near the end of the heated length and much lower for other SC or elevations. This means that the SC center temperature is not representative (i.e. lower) of the bulk temperature, the quantity actually calculated by ANTEO+ and SC codes in general. This is partially proven by the good agreement between the predicted and experimental clad temperature (Table III); error compensation between the SC temperature rise and the clad-coolant temperature difference predictions is a possibility but, alone, could not explain why the relative error drops from 11.9 to only 2.6 going from the SC to the clad.

From Table III it can also be seen how the correlations from "Mikityuk" and "Ma" perform similarly, both of them underpredicting the edge and corner pins temperatures. To increase the accuracy, a dedicated correlation for these types of pin must be used, like the one from [11].

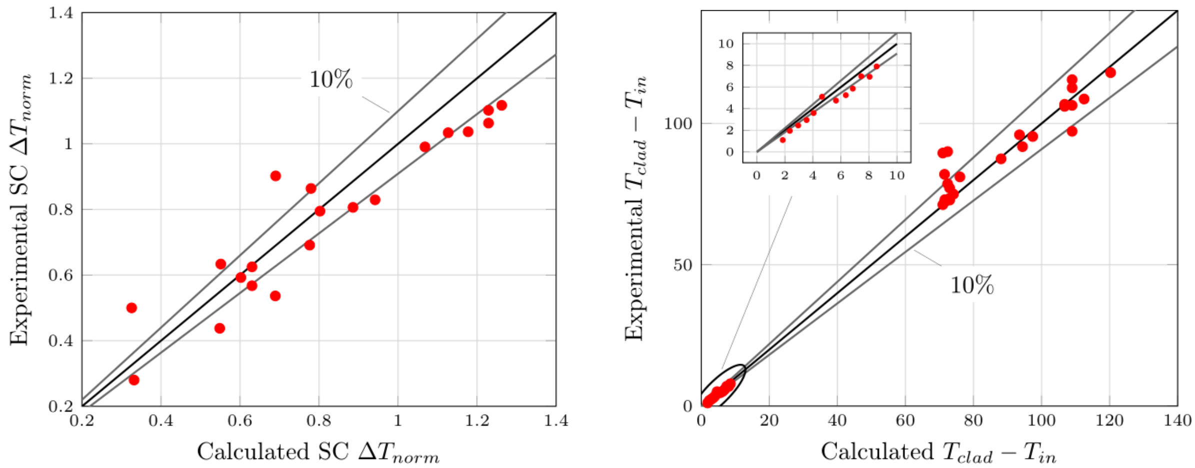

FIG. 5. Comparison of ANTEO+ vs. experimental data, in this validation campaign, for SC temperatures (left) and the outer clad temperature (right). Clad temperatures are obtained with the Mikityuk correlation.

TABLE VI: Comparison summary between simulations and experimental data used in this validation campaign.

		$\bar{\varepsilon}_{rel}$ [%]
ΔT_{norm} (20 points)		13.7
$T_{clad} - T_{in}$ (36 points)	Mikityuk[5]	9.8
	Ma[3]	9.5

4.2.KYLIN-II

The same considerations done in Section 4.1 hold true also for this bundle, because the SC temperature increase is lower than 7°C while the difference between the SC and clad temperatures is around 2°C and so, percentage-wise, relevant. Similarly to Section 4.1, the wire mixing effect is overestimated suggesting that, for HLMs, the correlations by [12] may not be directly transferable.

Even neglecting the thermal entrance region, the clad temperature is overestimated (*FIG.3*) due, partially, to a overprediction of the SC temperature but, mostly, to the error committed in estimating the thermal exchange between the coolant and the clad. The presence of the wire is aggravated by the low P/D of the bundle which enhances the thermal perturbation brought by the spacer. It must be noted that this is a local measurement – for a specific angular position of the pin – which oscillates when the wire is close to the thermocouple meaning, that the average clad temperature should agree better with ANTEO+ calculations [6]; nonetheless, correlations for the Nusselt's number based on bare rods are not reliable for tightly packed pins with a wire spacer.

[5] For edge and corner pins, when inside the correlation validity domain, the Nusselt's number has been evaluated by means of [11].

[6] The average clad temperature should lie somewhere between the minimum (when the wire is far away) and the maximum (when the wire is near the thermocouple) of the experimental data; this is, indeed, where the simulations results approximately lie (see *FIG.3* where the local increment is due to the wire presence).

4.3.CIRCE

This experimental set does not feature a wire spacer and so is useful to evaluate the accuracy of the Nusselt's correlations implemented in ANTEO+ [3]. The agreement with the experimental data is, overall, satisfactory (see *FIG.4*), with "Mikityuk" performing better than "Ma". Being the uncertainty, coming from the bifilar-type pin, on average, around 6.5% for the $T_{clad} - T_{in}$ temperature difference, the results in Table V can be better appreciated. The axial elevation 49.5 cm is in the middle of the spacer grid but, a decisive effect of the latter cannot be seen and lies within the experimental uncertainty.

4.4.Validation Overview

The SC temperatures are generally overestimated and the accuracy (error of 13.7%) substantially drops if compared to the previous validation campaign in sodium (compare Table I and Table VI). The motivations behind this have been discussed in Section 4.1. This is partially proven by the satisfactory agreement with the outer clad temperature, with an error around 9.8%, which is lower than the error committed on the SC temperature. This fact is even more apparent observing the error reduction, from 11.9% (on SC) to 4.8% (on clad), if the KYLIN-II data are not taken into account; these data, as explained in Section 4.2, represent a local measurement of a tight bundle with wire spacer.

5. Conclusions

The SC code ANTEO+, developed by ENEA, was previously validated on a large dataset mainly based, for what concerns the SC and clad temperatures, on sodium and sodium-eutectics experiments. In this work, the database has been extended to HLMC using the most recent experiments available from literature. The validation has contributed to the following considerations:

- The experiments used in the validation are not completely reliable for the SC temperatures comparison because the temperature at the SC center is not representative, for the selected bundles, of the bulk temperature.
- Within the limitations due to the previous point it seems that for edge and corner SCs the wire mixing effect is overestimated for HLMs.
- The clad outer temperature is calculated with reasonable agreement for a grid spaced bundle; for a wire spaced bundle, only the average temperature can be calculated with bare rods Nusselt's correlations. Local effects are not captured and specific correlations are needed to assess them, especially in tightly packed bundles.
- Edge and corner pins need specific Nusselt's correlations so to take into account the modified thermal exchange dynamics and, thus, to preserve accuracy. Very few of such correlations are available in the open literature, like the one in [11], but are characterized by a very limited application range.

Further experiments, designed with the objective of measuring a temperature representative of the SC bulk temperature (see [13]), are needed, so to verify the hypothesis put forward in the present work and to reliably assess the degree of confidence attributable to ANTEO+.

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