ON THE LIQUID METAL HEAT TRANSFER IN ANNULAR CHANNELS: REVIEW, PROPOSAL AND VALIDATION OF EMPIRICAL MODELS

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ABSTRACT

In this paper, liquid metal heat transfer under forced convection condition is investigated with the system code TRACE. TRACE is used to describe nuclear power plants or experimental facility with respect to the thermal-hydraulic behavior. The correct description of heat transfer must be assured for comprehensive and reliable investigations of liquid metal cooled installations. The majority of system codes used to simulate liquid metal heat transfer consider only circular pipe and bundle geometries, due to their prevailing application, by specific empirical heat transfer models. Annular channel type geometries are not represented yet. Therefore, uncertainties have to be considered if annuli are represented by a circular pipe. The improvement of TRACE with respect to heat transfer in annular channels is pursued. Hence, the present investigation is a valuable asset for the general liquid metal validation process of TRACE. In the present work, a literature review concerning experimental campaigns related to flow in annular channels is performed. The experimental data are investigated concerning their dependency on parameters like the Péclet number, the diameter ratio and the type of liquid metal (alkali metal versus heavy liquid metal). 19 experimental investigations are analyzed. An empirical Nusselt number correlation is proposed based on these data. This new heat transfer model includes the information of all experiments, aiming to provide a model which fits the general trend. The model is implemented into TRACE and experiments are post-test analyzed. In general, the results show a (very) good agreement between measurement and prediction from the qualitative and quantitative point of view. This investigation shows the necessity to provide specific empirical models in order to guarantee reasonable and reliable predictions.

1. INTRODUCTION

Heat transfer to liquid metals will be investigated with respect to annular geometries. Thereby, this study is tailored to the needs of thermal hydraulic investigations with the best estimate system code TRACE [1]. The present study is a continuation of liquid metal heat transfer research. In previous investigations, heat transfer capabilities for pipe and rod bundle geometries [2] and rectangular ducts and parallel plates [3] were implemented in TRACE and validated. The dedicated investigation of annular channels is the next logical step in the ongoing validation process of the system code TRACE. This research, in combination with the previous studies, will allows a comprehensive investigation of liquid metal cooled reactors and related facilities with TRACE. The considered geometries cover the entire range of components in such facilities like piping system, tanks, heat exchangers, fuel assemblies, etc.

To enable TRACE for the investigation of annular channels, suitable models must be provided. TRACE follows a 2-Fluid, 6-Equation approach, meaning that for the liquid and vapour phase of a coolant the conservation equations for mass, energy and momentum are solved. In case of liquid metals, the equation system is reduced to 3 equations, since only single phase flow is considered. In order to solve the energy conservation equation, information regarding the applied heat fluxes must be provided. In the present case, the wall-to-liquid heat transfer coefficient is needed. According to Eq. (1), the heat flux (q'') depends on the heat transfer coefficient (h) and the temperature difference between wall and liquid. The heat transfer coefficient is evaluated based on Eq. (2) and is a function of the Nusselt number, the thermal conductivity (k) and the hydraulic diameter (d_{hyd}). Thereby, the Nusselt number is a function of the Péclet number (Prandtl times Reynolds number) under forced convection conditions.

$$q''_{\mathrm{wall-to-liquid}} = h \cdot \left(T_{\mathrm{wall}} - T_{\mathrm{liquid}}\right) \tag{1}$$

$$h = \frac{k}{d_{\mathrm{hyd}}} \cdot \mathrm{Nu} \tag{2}$$

Furthermore, due to its empirical nature, the Nusselt number might also depend on geometrical parameters, like the diameter ratio ($D/d = \Delta$), indicated in Figure 1. The literature is reviewed to identify suitable experimental data. These data are evaluated and compared to each other in order to develop a suitable correlation for the determination of the particular Nusselt number for annular channels. The Nusselt correlation is then implemented into TRACE. The heat transfer coefficient and the wall temperature are calculated according to Eq. (2) and (1), respectively.

2. LITERATURE REVIEW

Baker and Sesonske [4] investigated NaK flow in a tube and a concentric annulus. The annulus had a diameter ratio (Δ) of 2.1. Nusselt number values have been reported for Péclet numbers between 100 and 1100. The experimental data can be fairly well represented by the empirical Nusselt correlation of Werner et al. [5].

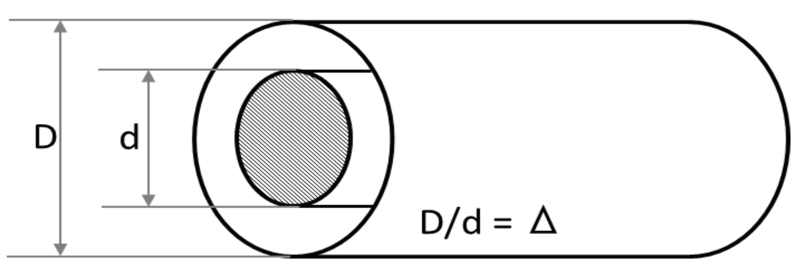

Figure 1 Annular channel schematic

Borishanskiy et al. [6] published experimental data for annuli with diameter ratios of 1.37 and 1.55 where heating was realized from the inside, the outside or from both sides. Cases with combined heating show higher heat transfer coefficients, while cases with internal and cases with external heating are very similar. Unfortunately, they did not specify which liquid metal was used neither did they mention the Prandtl number and temperature (range). Therefore, the data are only used for deriving a suitable model but cannot be used for the validation of TRACE.

Chen and Yu [7] published a paper with respect to entrance effects in liquid metal cooled annuli. For validation purposes, they used unpublished data of Nimmo et al. for mercury flow. In the 1960s, Dwyer and Tu and Yu and Dwyer published a series of papers [8, 9, 10, 11 and 12] dealing with concentric and eccentric annuli. They used semi-empirical correlations for calculating the Nusselt number values as a function of the Péclet number on the bases of heat transfer in circular tubes and parallel plates. A Nusselt number correlation provided by them is used in this analysis

Foust [13] published a handbook for sodium and sodium-potassium alloy in which unpublished data of Nimmo et al. for mercury flow are reported. Hall and Jenkins [14] investigated sodium and sodium-potassium alloy flow in double annular channels with in total three flow channels (inner tube plus two annular channels around) the inner annular channel was characterized by a diameter ratio of 1.36. The data fit well together to other experimental results. Hartnett and Irvine [15] estimated Nusselt numbers for noncircular ducts, among them concentric annuli.

Hlavac et al. [16] investigated the effect of wetting in a mercury cooled annulus with the aim of comparing values for eddy diffusivity of heat and momentum. Khabhakhpasheva and Il'in [17] performed experiments with sodium-potassium alloy in annular channels with diameter ratios of 1.4, 1.7 and 2.1. In contrast to other experiments, the heat was applied to the outer wall, while the inner one was isolated. Their results agree well with the ones with inner heating. Furthermore, the effect of the diameter ratio on the results is rather small.

Lee [18] performed analytical investigations of concentric annuli with emphasize on thermal entry effects. The analysis showed that developed flow is obtained after roughly 30 hydraulic diameters and that a small dependency of the diameter ratio exists on the developing length. Lubarsky [19] investigated lead-bismuth eutectic in a combined tube and annulus test section. In some test cases, the lead-bismuth eutectic was enriched with magnesium (max 0.04 wt %). In general, lower Nusselt numbers, as for similar experiments, were obtained.

Lyon reported experimental data [20] for three diameter ratios (1.23, 1.37 and 1.43) and an empirical correlation [21]. Sodium-potassium alloy was the coolant. No influence of the diameter ratio on the Nusselt number is visible. Marocco et al. [22] performed experiments in an annular cavity with a diameter ratio of 7.35. The experimental setup is more like a single heated rod in a tube. The effect of the developing flow was the subject of investigation.

Miyazaki et al. [23] investigated lithium flow under traverse magnetic fields. For the sake of comparison, experimental data have been reported for cases without magnetic field. Variations within the experiments are caused by the different thermocouple position in circumferential direction but the general trend agrees very well with other experiments. Petrovichev [24 and 25] investigated mercury flow through annular channels with three different diameter ratios, 1.55, 1.67 and 2.07. Water was flowing in the inner tube and around the annular channel. For the test section with Δ = 1.55 external and internal cooling was investigated resulting in an identical heat transfer behavior. A clear increase in the Nusselt number was observed for increasing diameter ratios. In addition, an empirical model was proposed to fit the experimental data.

R. Qiu [26] investigated the heat transfer in an annulus during forced convection with developing and developed flow. All experiments have been performed with sodium flowing through an annulus with a diameter ratio of 1.85. The Reynolds number ranged from 6000 to 60000. Qui also developed Nusselt number correlation which fits to his experimental data. The most recent experiment has been elaborated by Z. Qiu et al. [27]. Test sections with diameters of 1.50 and 1.67 were used with sodium as coolant. That study is the only on in the low Péclet number range (5-85). It is one of the few experiment were measurement uncertainties are available. These are less than 0.75 % for temperature, mass flow rate and heat flux. Seban and Casey [28] dealt with lead-bismuth eutectics in annular channels with a diameter ratio of 1.3 and 1.74.

Subbotin et al. [29] performed experiments with mercury in narrow annular channels (Δ < 1.10). One of their findings was that the diameter ratio has an influence on the Nusselt numbers where smaller diameter ratios yield higher Nusselt numbers at the same Péclet number. Furthermore, they investigated the difference between a regular heated annulus (inner wall heated) and one which is heated from both walls. The experiments with two-side heating are characterized by higher total heat transfer coefficients. In addition, the experimental data are compared to the empirical Nusselt correlation of Buleev [30] and Harrison and Menke [31].

Subbotin et al. [32] investigated the effect of the eccentricity of the inner pipe of an annulus (Δ = 1.12) on the heat transfer behavior. Values for a concentric annulus are reported as well as reference. Furthermore, the influence of ribs in the annular cavity is addressed. Thereby, the ribless flow channel is characterized by higher heat transfer rates than the one with ribs. Trefethen [33] used also a combined tube and annulus test section with mercury flowing through both channels. Several test sections were used with diameter ratios of 1.17, 1.39, 1.75 and 2.31. For the first three diameter ratios, no differences are visible for the Nusselt number. Only for the largest diameter ratio, considerably higher Nusselt numbers are reported.

Uda et al. [34] studied the heat transfer behavior to lithium in a circular channel with a central heating pin (diameter ratio equal to 5.27) under transverse magnetic fields. The experimental data without a magnetic field agree well with other experimental data.

Werner et al. [5] used a test section with a tube and a concentric annulus with sodium-potassium flowing in both channels. Furthermore, two different test sections (A and B) have been used. The main difference between test section A and B are the initial velocity profile. In test section A the profile was between flat and fully developed while for test section B the profile was essentially flat. Data are reported for more than 50 hydraulic diameters downstream the inlet.

A more recent account on heat transfer in annular channels is given by Xiao et al. [35]. In a sodium cooled annular channel with a diameter ratio of 1.54 heat transfer values have been recorded for a Péclet number range of 200 to 800.

An overview of all available experimental data is given in Table 1 and in Figure 2.

Table 1 Overview of available experimental data

Reference	*Δ*	Coolant	Pe
Baker and Sesonske [4]	2.10	NaK	110 – 1100
Borishanskiy et al. [6]	1.37, 1.54	?	400 – 4000
Hall and Jenkins [14]	1.36	Na, NaK	70 – 800
Khabakhpasheva and Il'in [17]	1.40, 1.70, 2.10	NaK	300 – 1200
Lubarsky [19]	1.25	LBE	300 – 1300
Lyon [20]	1.23, 1.37, 1.43	NaK	50 – 600
Marocco et al. [22]	7.35	LBE	5500
Miyazaki et al. [23]	2.08	Li	200 – 1800
Nimmo et al. [7]	2.78	Hg	450 – 10000
Petrovichev [24, 25]	1.55, 1.67, 2.07	Hg	650 – 5000
R. Qiu [26]	1.85	Na	30 – 350
Z. Qiu et al. [27]	1.50, 1.67	Na	5 – 85
Seban and Casey [28]	1.30, 1.74	LBE	400 – 2000
Subbotin et al. [29]	1.05, 1.09	Hg	200 – 3000
Subbotin et al. [32]	1.12	NaK	40 – 750
Trefethen [33]	1.17, 1.37, 1.73, 2.31	Hg	50 – 850
Uda et al. [34]	5.27	Li	700 – 2250
Werner et al. [5]	1.83	NaK	60 – 800
Xiao et al. [35]	1.54	Na	200 – 800

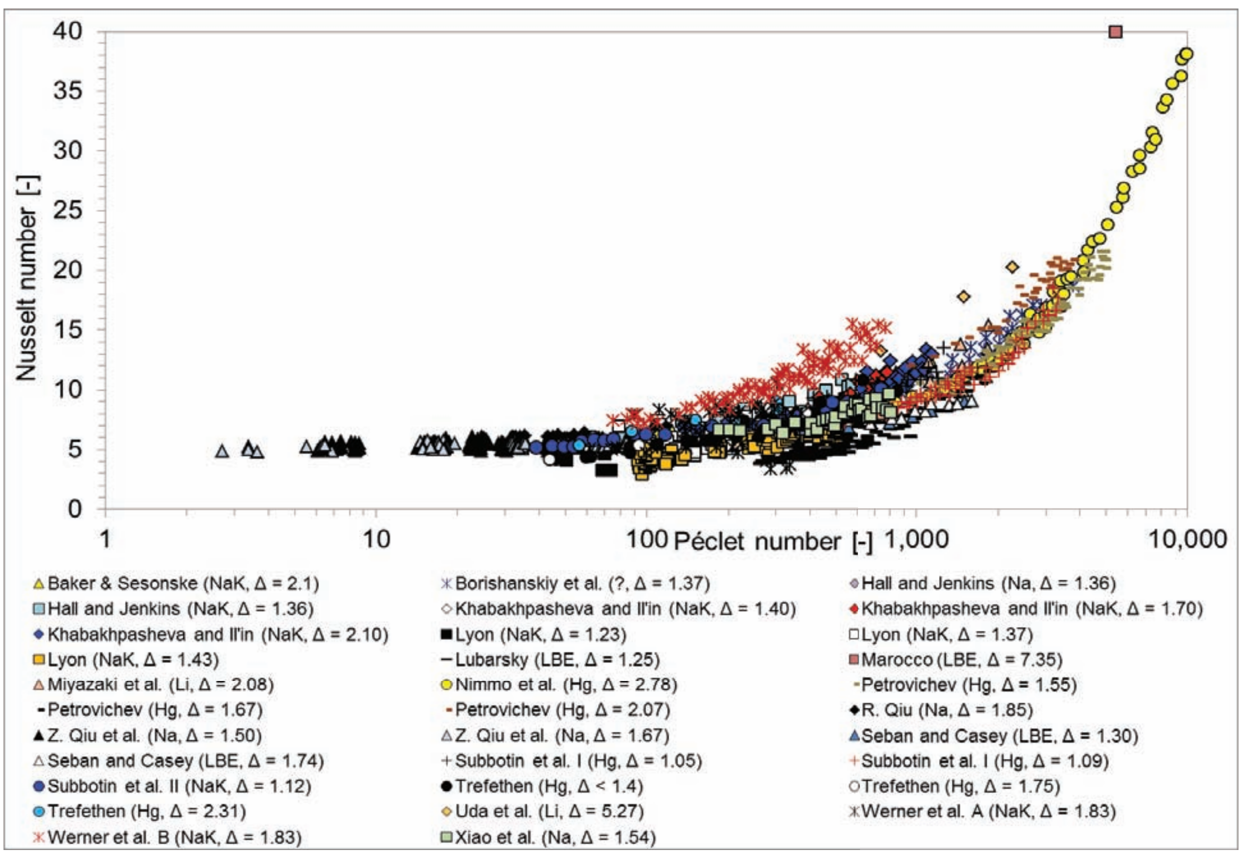

Figure 2 Experimental Nusselt number as a function of Péclet number

In total 19 experiments with 31 diameter ratios (1.05 – 7.35) and 5 different fluids are found (Na, NaK, LBE, Li, Hg). The Péclet number ranged from 50 to 10000. It is interesting to note that the majority of the experiments was performed before the 1970's (1950's = 6; 1960's = 6; 1970's = 0; 1980's = 2, 1990's = 0; 2000's = 2; 2010's = 2). In general, the experiments are consistent with each other. Only the experiment of Lubarsky [16] undershoots the general trend while Werner et al. [2] overshoots it (taking into account that the Nusselt number might be a function of the diameter ratio). Furthermore, some of the experiments are characterized by a large spread of the recorded data points.

Based on the experimental data, one new Nusselt number correlation is developed. Besides the dependency on the Péclet number it also has a dependency on the diameter ratio. This new model is compared to other available Nusselt number correlations. Over the years, these correlations (Table 2 and Figure 3) have been proposed by different authors. Half of the correlations include a dependency of the diameter ratio while the other half does not.

Table 2 Overview of available empirical Nusselt correlations

Reference	Correlation	Range
Buleev [30]	$\mathrm{Nu} = 5.10 + 0.02 \cdot \mathrm{Pe}^{0.8}$	-
Dwyer [9]	$\mathrm{Nu} = [4.82 + 0.697 \cdot \Delta] + 0.0222 \cdot \mathrm{Pe}^{0.758 \cdot \Delta^{0.053}}$	Δ = 1-7, Pe = 50 – 10^4
Harrison [31]	$\mathrm{Nu} = 4.90 + 0.0175 \cdot \mathrm{Pe}^{0.8}$	-
Lyon [21]	$\mathrm{Nu} = 0.75 \cdot \Delta^{0.3} \cdot (7.0 + 0.025 \cdot \mathrm{Pe}^{0.8})$	$\Delta > 1.4$
Petrovichev [24]	$\mathrm{Nu} = \Delta^{0.3} \cdot (4.3 + 0.015 \cdot \mathrm{Pe}^{0.8})$	Pe = 500 – 5000
R. Qiu [26]	$\mathrm{Nu} = 5.75 + 0.022 \cdot \mathrm{Pe}^{0.8}$	-
Seban [28]	$\mathrm{Nu} = 5.80 + 0.02 \cdot \mathrm{Pe}^{0.8}$	$\Delta \leq 1.4$
Werner [5]	$\mathrm{Nu} = 0.80 \cdot \Delta^{0.3} \cdot (5.12 + 0.0296 \cdot \mathrm{Pe}^{0.785})$	$\Delta > 1.4$
This study	$\mathrm{Nu} = \Delta^{0.3} \cdot (4.75 + 0.0175 \cdot \mathrm{Pe}^{0.8})$	Δ = 1-7, Pe = 10 – 10^4

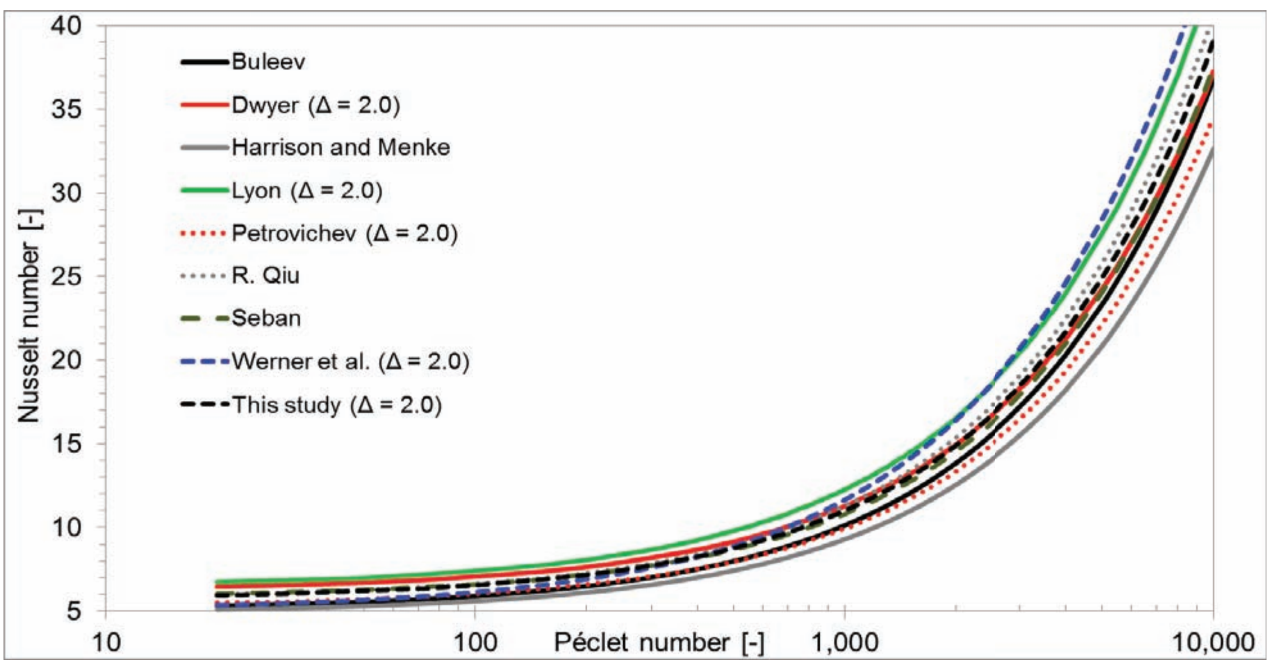

Figure 3 Nusselt number versus Péclet number based on available empirical correlations

That can be explained by the fact that the developers of different correlations did not always use multiple experimental sources. For instance R. Qui [26] used his own data, with just one diameter ratio, to derive an empirical correlation. The new proposed correlation is based on all data points found in the literature.

In addition, the experimental data are averaged and sorted depending on the type of meatal used; alkali metals with sodium, sodium-potassium alloy and lithium, and heavy liquid metals with lead bismuth eutectics and mercury, Figure 4. A distinction between alkali metals (Na, NaK and Li) and heavy metals (Hg, LBE) could be assumed since alkali metals deliver higher Nusselt numbers at identical Péclet numbers and diameter ratios than heavy metals do. The experimental data for alkali metals agree well among each other, while for heavy metals larger discrepancies are visible. One reason can be the problem of surface wetting which is of crucial importance for a proper heat transfer. In general, experiments with heavy liquid metals suffer more from non-wetting problems.

3. VALIDATION AND VERIFICATION

To verify the correct implementation and to assess the validity of the proposed Nusselt number correlation aforementioned experiments are computed. The comparison of experimental data with prediction for each case is given in Figure 5 to Figure 7. In addition, the fraction of data points within a certain range is given, too. The experiment of Borishanskiy et al. [6] is not modelled since the liquid metal used is unknown. Furthermore, the considered data of the Marocco et al. [22] experiment consist of only one Nusselt number value (one constant Péclet number) which makes a dedicated plot dispensable. The measured Nusselt number was around 40 and the calculated one is 39.6, which is in almost perfect agreement to the experiment.

In general, the comparison between experiment and prediction shows a (very) good agreement. Nevertheless, some discrepancies are visible. A tendency to over predict is evident for the experiments with heavy liquid metals.

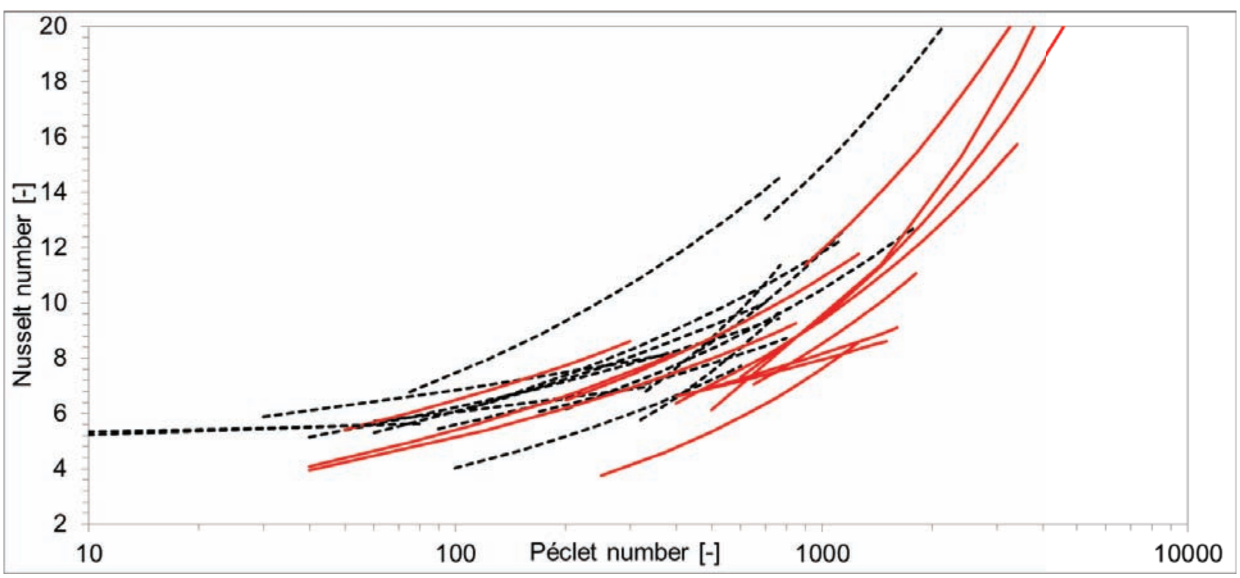

Figure 4 Comparison between alkali metals (broken black curves) and heavy liquid metals (solid red curves)

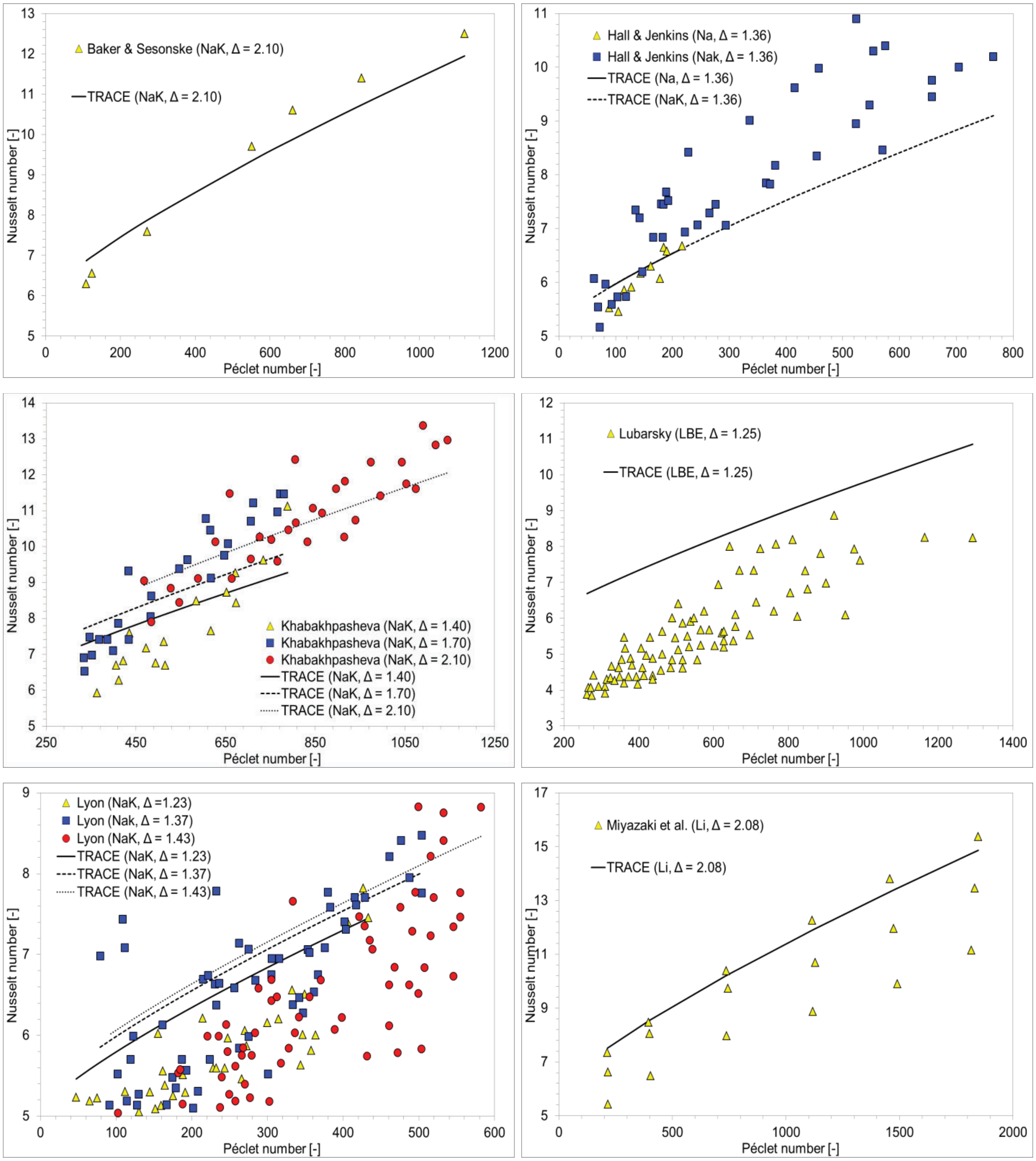

Figure 5 Experimental and predicted Nusselt number as a function of the Péclet number for various experiments

That might be related to the mentioned problems arising due to non- or partial wetting of the surface. For the alkali metal cases all predictions, except for the Werner et al. case B [6], are in a very good agreement to the experiment. As mentioned above, the velocity profile in case B was not developed, but flat, which causes higher heat transfer coefficients.

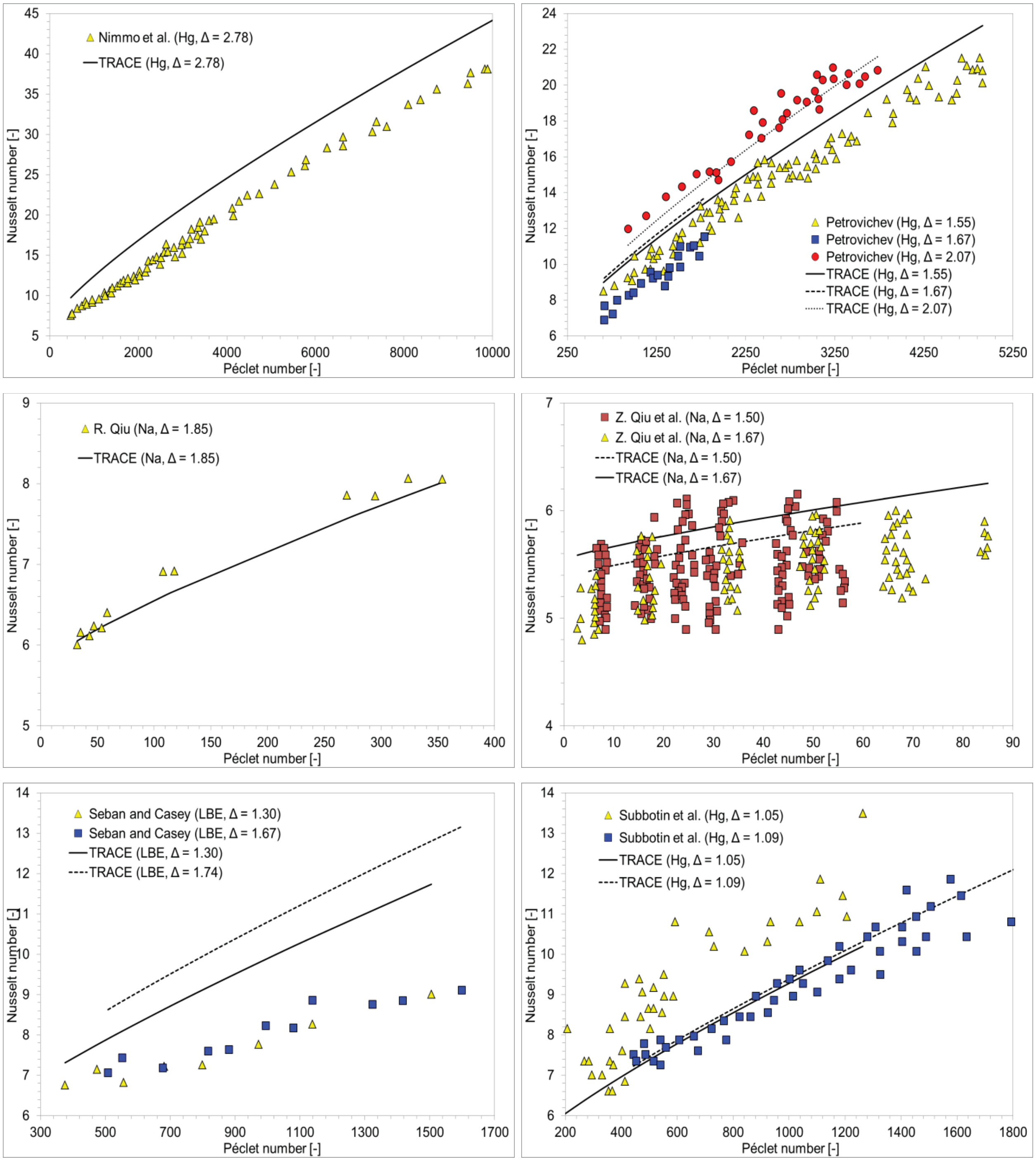

Figure 6 Experimental and predicted Nusselt number as a function of the Péclet number for various experiments (cont.)

To confirm the good qualitative evaluation, several quantitative measures are calculated. These are the coefficient of determination (R), the covariance and the correlation (COV and COR), the mean absolute error (MAE), the average relative error (ARE), the root square mean error (RSME), and the standard deviation (SD). All of them are plotted in Table 3. The calculation of that many measures is reasonable since only one measure could lead to a wrong impression. For the third case of Lyon [20] (Δ = 1.43) the ARE is 27.44 which is very high. It suggests a very large discrepancy between experiment and prediction. But all other quantitative measures and the qualitative impression indicate a good agreement. The large error arises from the rather large spread of the experimental data points.

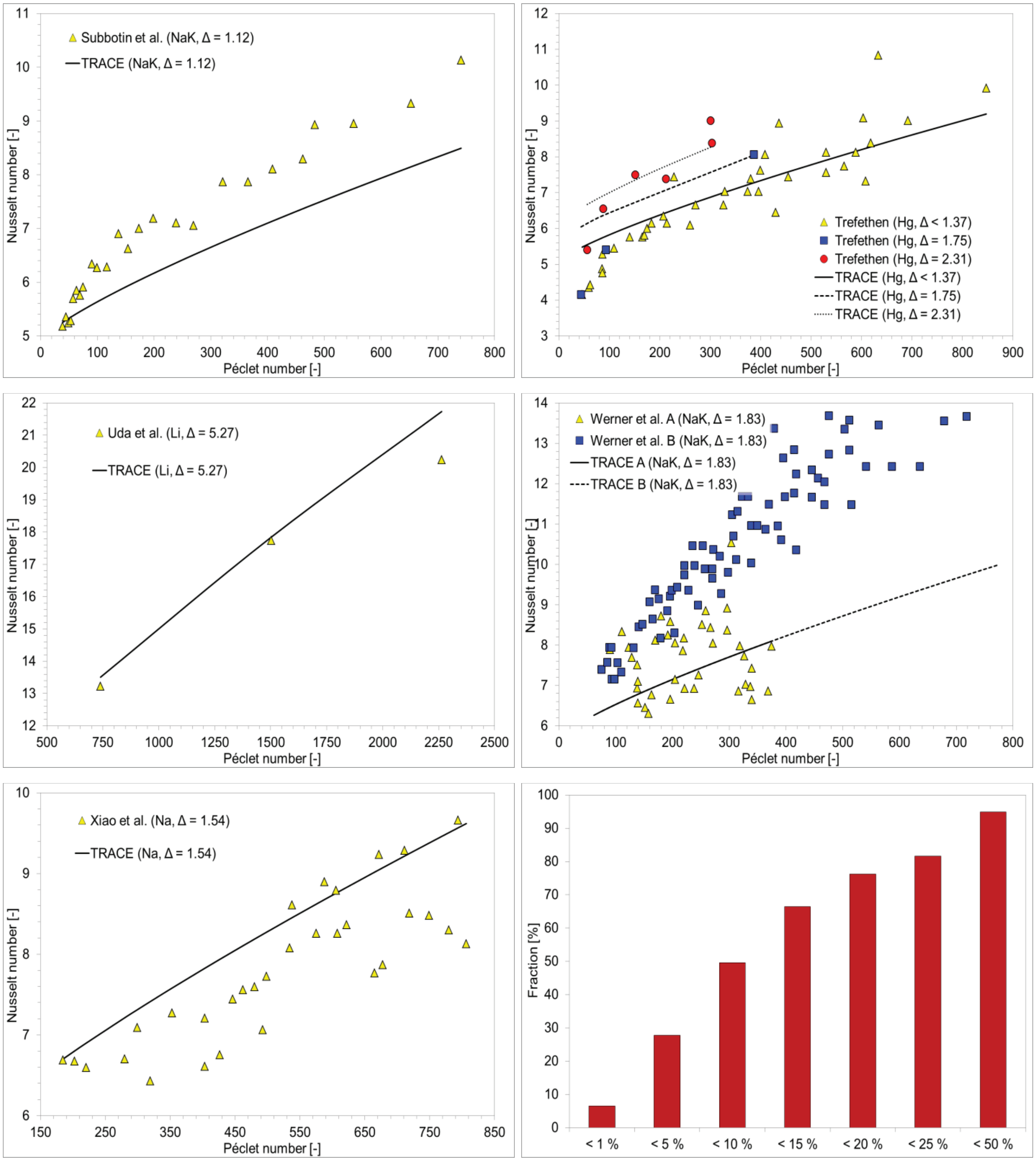

Figure 7 Experimental and predicted Nusselt number as a function of the Péclet number for various experiments (cont.) and fraction of the data points within a certain range (bottom right)

Table 3 Quantitative and qualitative evaluation of the validation cases

Ref.	Δ	Coolant	R	COV	COR	MAE	ARE	RSME	SD	QE
[4]	2.10	NaK	0.85	4.05	1.00	0.51	-0.21	0.53	0.03	++
[14]	1.36	Na	0.84	0.09	0.94	0.21	2.63	0.27	0.03	+
[14]	1.36	NaK	0.88	1.36	0.91	0.88	-8.65	1.11	0.47	o
[17]	1.40	NaK	0.85	0.76	0.90	0.82	6.35	0.97	0.29	+
[17]	1.70	NaK	0.91	1.07	0.95	0.89	-2.03	0.84	0.27	+
[17]	2.10	NaK	0.84	1.07	0.87	0.60	-0.66	0.76	0.24	++
[19]	1.25	LBE	0.86	0.99	0.87	2.40	46.92	2.49	0.44	-
[20]	1.23	NaK	0.83	0.44	0.85	0.92	18.74	1.05	0.27	+
[20]	1.37	NaK	0.77	0.51	0.78	0.67	8.71	0.83	0.24	++
[20]	1.43	NaK	0.89	0.98	0.90	1.37	27.44	1.52	0.44	+
[22]	7.32	LBE	-	0.00	-	0.42	-1.06	0.42	0.30	++
[23]	2.08	Li	0.83	6.05	0.88	1.35	13.96	1.76	1.36	+
[7]	2.78	Hg	0.98	82.31	1.00	4.11	24.98	4.21	0.82	o
[24]	1.55	Hg	0.97	13.52	0.98	1.32	8.84	1.51	0.54	+
[24]	1.67	Hg	0.91	1.71	0.95	2.30	25.05	2.33	0.19	o
[24]	2.07	Hg	0.94	6.79	0.97	0.62	-2.18	0.77	0.21	++
[26]	1.85	Na	0.91	0.59	0.99	0.13	-1.63	0.17	0.01	++
[27]	1.50	Na	0.24	0.01	0.24	0.30	3.57	0.36	0.04	++
[27]	1.67	Na	0.56	0.03	0.57	0.47	8.69	0.52	0.06	+
[28]	1.30	LBE	0.85	0.97	0.97	1.58	20.39	1.73	0.57	o
[28]	1.74	LBE	0.87	0.94	0.95	2.66	32.52	2.77	0.65	-
[29]	1.05	Hg	0.88	1.70	0.90	1.35	-13.89	1.54	0.55	o
[29]	1.09	Hg	0.96	7.18	0.98	0.48	2.12	0.63	0.18	++
[32]	1.12	NaK	0.94	1.28	0.98	0.73	-9.31	0.85	0.20	o
[33]	1.37	Hg	0.89	1.39	0.92	0.57	3.92	0.76	0.26	++
[33]	1.75	Hg	0.66	1.41	0.99	0.97	21.30	1.24	0.89	o
[33]	2.31	Hg	0.79	0.69	0.95	0.50	3.76	0.64	0.19	+
[34]	5.27	Li	0.66	9.66	0.99	0.63	3.36	0.88	0.58	++
[5]	1.83	NaK	0.22	0.17	0.22	1.23	13.33	1.58	0.97	++
[5]	1.83	NaK	0.93	1.92	0.95	3.00	-26.13	3.29	1.82	--
[35]	1.54	Na	0.81	0.61	0.84	0.59	7.22	0.73	0.19	o

QE classification: (++) excellent; (+) good; (o) satisfactory; (-) sufficient; (--) deficient

4. SUMMARY AND CONCLUSION

Several experiments investigating the heat transfer to liquid metals in annular geometries are studied. 19 experiments with 31 combinations of coolants and diameter ratios are found. In total, more than 1000 data points are used. Based on these experiments, an empirical Nusselt number correlation is developed. This correlation depends on the diameter ratio and the Péclet number,

$$\mathrm{Nu}_{\mathrm{annulus}} = \Delta^{0.3} \cdot (4.75 + 0.0175 \cdot \mathrm{Pe}^{0.8}), \tag{3}$$

and is valid for diameter ratios of up to 7 and Péclet numbers up to 10000. This correlation is implemented into the TRACE source code. This allows the complete analysis of experimental facilities with liquid metals flowing through various channel geometries.

The mentioned experiments are modelled with TRACE to verify and validate the proposed Nusselt number correlation. The qualitative and quantitative evaluation of the comparison between experiment and prediction is “good” (B or 2) in terms of school grades. Furthermore, more than 75 % of all data points are within the ± 20 % uncertainty range. With respect to the range of application of a system code and the complexity of the liquid metal heat transfer, an important and necessary extension of the existing empirical models for liquid metal heat transfer has been made.

Visible discrepancies between experiment and prediction are related to experimental conditions. In one case, Werner et al. case B, the velocity field was not developed. For undeveloped flow, higher heat transfer coefficients are observed than for developed flow. Therefore, the model for developed flow will predict lower than measured values. In addition, experiments are always influenced by uncertainties. Among these are: geometric deviations, entrainment of gas, impurities in the coolant, input and boundary conditions, material properties, measurement techniques, physical models, thermos-physical properties and surface wetting. In TRACE, and system codes in general, perfect conditions like a constant mass flow rate or perfect surface wetting are assumed. Hence, deviations between experiment and prediction are unavoidable. To cope with that, uncertainty and sensitivity studies have to be performed. That would increase the number of simulations per experimental case from 1 to around 100 (depending on the statistical fidelity).

The next step of the validation process of TRACE is the extension from pure forced convection to free and mixed convection. Even though such heat transfer regimes are very seldom applied, it must be considered during safety related investigations. During operational transients like start-up or shut-down, and during accidents, heat transfer regimes different to forced convection are present. Furthermore, the heat transfer during undeveloped thermal and velocity fields will be investigated in the near future. Also, the already mentioned influence of the uncertainties regarding, e.g., boundary conditions will be addressed in the next investigations.

5. ACKNOWLEDGEMENT

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