MIXED CONVECTION WITH LIQUID METALS: REVIEW OF EXPERIMENTS AND MODEL DEVELOPMENT

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ABSTRACT

In this paper, a review of experiments related to liquid metal heat transfer under mixed convection is performed. This study is relevant because heat transfer during start-up and shut-down procedures, and operational transients is influenced by natural convection, resulting in mixed convection, which differs considerably from forced convection. Up to now, simulation tools like TRACE, RELAP, etc. apply only forced convection models for liquid metal heat transfer. The influence of mixed convection on the heat transfer during the above mentioned transients is completely ignored. Hence, it is not possible to simulate mixed convection with best-estimate system codes like TRACE or RELAP. In order to perform realistic simulations of plants and experimental facilities mixed convection must be addressed and considered. Therefore, the literature is reviewed for experimental data with liquid metal heat transfer under mixed convection and generally applicable statements and models will be provided. A clear distinction in the heat transfer behavior for low and high Péclet number flows can be identified. Thereby, a Péclet number dependency is visible for higher Péclet numbers (Pe > 100). Furthermore, the heat transfer (Nusselt number) cannot be presented as a function of one dimensionless parameter. To identify underlying phenomena, especially when comparing different experimental scenarios several dimensionless numbers are needed (Gr*, B, Z, etc.). Based on this study, it is possible to derive a model for the heat transfer under mixed convection. Nevertheless, these findings and the sparse number of experiments also indicate the need for new and comprehensive experiments.

KEYWORDS
Liquid metal heat transfer, mixed convection, empirical models

1. INTRODUCTION

The investigation presented here is part of the LIMCKA and SESAME activities. LIMCKA (LIquid Metal Competence center KArlsruhe) is a recently established consolidation of the different liquid metal research groups and initiatives at the Karlsruhe Institute of Technology (http://limcka.forschung.kit.edu/index.php). Due to the manifold of liquid metal related research fields (thermo hydraulics, heat transfer, magneto hydro dynamics, material development) and the different fields of application (fission, fusion, concentrated solar power, thermal storages) an integrated presentation of the activities was missing. LIMCKA will provide a common platform for liquid metal related research at the KIT. With respect to the European SESAME project (The thermal-hydraulics Simulations and Experiments for the Safety Assessment of Metal cooled reactor) [1] the work is related to work package 1 (fluctuations and vibrations). Thereby, the development of (empirical) models for the application in simulation tools is pursued. In this context, the heat transfer to liquid metals during mixed convection is investigated.

Mixed convection is one of the three convective heat transfer regimes. Thereby, mixed convection is present when forced convection is combined with natural convection. Forced convection is typically caused by a pump or a pressure difference in a system, while natural convection is caused by buoyancy effects. The density variations as a consequence of the free convection alter the heat transfer behavior. In principle, the buoyancy effects distort the velocity profile in radial direction of the flow channel, which then cannot be considered forced convection anymore [2]. Hence, the combination of both convective heat transfer regimes will differ from pure forced and pure natural convection. Thereby, the mixed convection can either enhance (buoyancy aided) or impair (buoyancy opposed) the heat transfer with respect to forced convection. This behavior is visible in many experimental studies [3, 4, 5, 6]. Cotton et al. [6] provided a qualitative dependency of the buoyancy parameter on the heat transfer. Figure 1 shows the qualitative behavior for low and high Péclet numbers and for upward and downward flow. Upward or ascending flows are characterized by a small impairment followed by an enhancement of the heat transfer, represented by the Nusselt number ratio (mixed convection over forced convection). The impairment is more pronounced for high Péclet numbers. For descending or downward flows with high Péclet numbers a steady increase of the Nusselt number ratio is visible with increasing buoyancy parameter. For low Péclet numbers the heat transfer is first enhanced and is later decreased with increasing buoyancy parameter. In principle, this qualitative behavior is presented also by other authors [5, 7, 8].

This behavior is usually not considered when doing thermal-hydraulic analyses of liquid metal cooled reactor concepts and experimental facilities with best-estimate system codes like TRACE, RELAP, CATHARE, etc. Pure forced convection is assumed, even though the presence of mixed convection is at least very likely. Mixed convection might be present during each transient where a clear reduction of the mass flow rate is accompanied by a large heat load. An examples is the reduction of the pump speed, while the heat source is still at full power. Furthermore, during start-up and shut-down transients, mixed convection might be present. In addition, even during normal full power operation mixed convection might be present in, say, a rod bundle sub channel with the very high heat loads.

2. LIQUID METAL HEAT TRANSFER UNDER MIXED CONVECTION

A simple mean to evaluate if natural convection is influencing forced convection is the calculation of the Richardson number (Ri), which is the Grashof number (Gr) divided by Reynolds (Re) squared. Furthermore, several other quantities exist to evaluate the presence of mixed convection. To identify scenarios with buoyancy effects on forced convection Buhr et al. [9] proposed the Z_1 parameter.

$$Z_1 = \frac{\mathrm{Ra}}{\mathrm{Re}} \cdot \frac{d}{l}, \tag{1}$$

where Ra is the Raleigh number, Re is the Reynolds number, *d* is the pipe diameter and *l* is the test section length. Buhr et al. [9] claim that at $Z_1 > 2 \cdot 10^{-3}$ free convection is influencing the forced convection heat transfer. Besides the above given expression for the Z parameter a second definition exists in the literature [10]:

$$\mathrm{Z}_2 = \sqrt[4]{\frac{\mathrm{Gr}^*}{4 \cdot \mathrm{Re}}}, \tag{2}$$

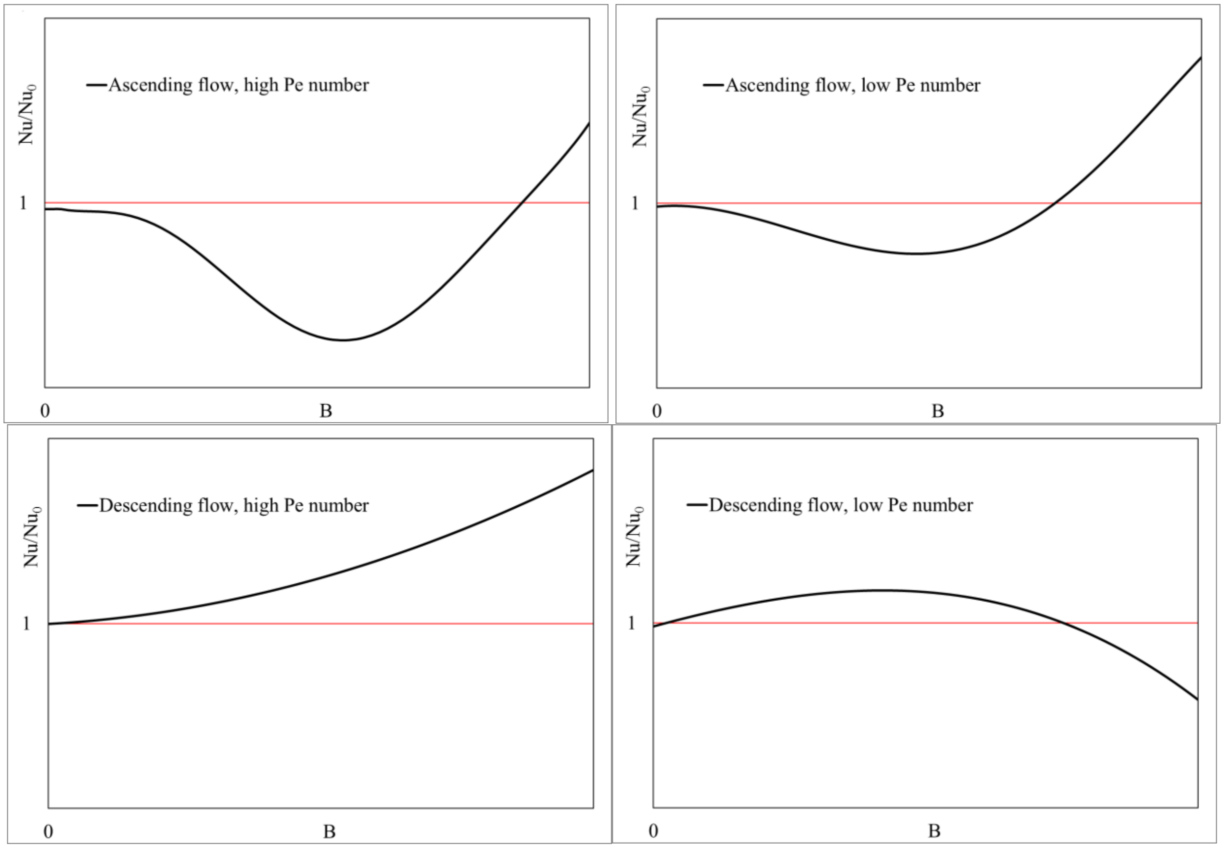

Figure 1. Qualitative trend of the heat transfer enhancement/impairment due to buoyancy aided/opposed flows for high and low Péclet numbers.

where Gr* is the modified Grashof number, which writes as follows:

$$\mathrm{Gr}^* = \frac{\beta \cdot g \cdot d^4 \cdot q \cdot \rho^2}{\eta^2 \cdot k} = \frac{\beta \cdot g \cdot d^4 \cdot \frac{\partial T}{\partial l} \cdot \rho^2 \cdot c_p}{\eta \cdot k} \cdot \frac{\mathrm{Re}}{4}, \tag{3}$$

where β is the thermal expansion coefficient, g the acceleration of gravity, d is the pipe diameter, q is the heat flux density, ρ is the density, $\partial T/\partial l$ is the axial temperature gradient, c_p is the specific heat, η is the dynamic viscosity, k is the thermal conductivity and Re is the Reynolds number. Another dimensionless parameter found in the literature accounting for buoyancy effects is the buoyancy parameter B introduced by Walton et al. [11] and Jackson et al. [12].

$$\mathrm{B} = \frac{\mathrm{Gr}^*}{\mathrm{Re}^{1.825} \cdot {\mathrm{Nu}_0}^2}, \tag{4}$$

where Gr* is the modified Grashof number and Nu_0 is the Nusselt number under forced convection condition. The buoyancy parameter B and the Z_2 parameter correlate with the following relationship. This allows a relatively quick comparison of buoyancy affected heat transfer coefficients and Nusselt numbers found in the literature.

$$B = \frac{4 \cdot \mathrm{Re} \cdot Z_2{}^2}{\mathrm{Re}^{1.825} \cdot \mathrm{Nu}_0{}^2}, \qquad (5)$$

The following correlation, based on the work of Subbotin et al. [13], for turbulent forced convection in a pipe is used:

$$\mathrm{Nu}_0 = 5 + 0.025 \cdot (\mathrm{Re} \cdot \mathrm{Pr})^{0.8}, \qquad (6)$$

Where Pr is the Prandtl number and Re is the Reynolds number. This correlation is valid for: $\mathrm{Pr} < 0.1$ and $10^4 \leq \mathrm{Re} \leq 5.0 \cdot 10^6$. Although delivering good results, it is not the actual recommendation of [14, 15]. Nevertheless, this correlation is chosen because: 1) the comparison to the recommendation shows only small discrepancies and 2) this correlation is used by the authors of [11, 12], which proposed Eq. (5). A detailed account on liquid metal heat transfer is found in [16].

With respect to mixed convection, several Nusselt number correlations exist but none of them has been applied to more than one experimental campaign, meaning that a general applicability is not given. Therefore, these models are not recited here but examples are given, among others, in [7, 10, 12].

Hence, no Nusselt number model with general applicability is available, which asks for the development of one. In case a general model is not available, one should try to develop particular ones, like models valid for alkali or heavy liquid metals, or low and high Péclet number flows. To do so, the review of available experimental data is inevitable.

3. REVIEW OF EXPERIMENTS

One of the main objectives of this contribution is to provide a list as complete as possible of available experiments related to liquid metal heat transfer under mixed convection conditions (see Table 1). The actual number of experiments is rather small. In total 11 different experimental campaigns have been found, with the restriction that some of them have been performed at the same facility but by different researchers. Table I provides the vital information of these experiments and the corresponding literature. One interesting fact is that the magnitude of the experiments has been performed in the late 1960's – early 1970's. The authors do not claim to provide a complete table but more recent result have simple not been found.

Ampleyev et al. [17] (1969)

Ampleyev and colleagues investigated forced and mixed convection in a sodium-potassium cooled loop. In addition, the heat transfer development as a function of the distance from the flow channel inlet is reported, too. The test section is a vertical pipe with an internal diameter of 50 mm and an active length of 2700 mm. Péclet numbers between 10 and 3000 are investigated. Unfortunately, they did not specify the Péclet numbers at which their experimental data for mixed convection are recorded. During the experiments Ampleyev and colleagues encountered appreciable heat loss especially at low Péclet numbers ($\mathrm{Pe} < 100$). The difference between the electrical power used for the experiment and the measured thermal power is in the range of 3 to 7 %. Hence, the data, especially relevant for mixed convection, might be influenced by larger than usual heat losses. With respect to mixed convection they found out that their experimental data are below a theoretical limit. Unfortunately, it is not possible to determine the theoretical work they are using due to typos in the original paper. Furthermore, they show that the flow becomes turbulent even at $\mathrm{Re} = 400$. One of the main issues with their Nusselt number as function of Z data are the rather large discrepancies among the data. For example, at $Z = 10$ the Nusselt number is 5.5 in one case and in the other 10. With no information on the corresponding Péclet number it is difficult to identify the reason for the deviations.

Table I. Main parameters of experiments with mixed convection

Author	**Fluid**	**L/d**	**Pe**	**Chan.**	**Flow**	**Year**	**Ref**
Ampleyev et al.	NaK	40	10 – 3000	Pipe	↑↓	1969	[17]
Brukx et al.	Na	… 6	50	Pipe, Annulus	↑↓	1976	[18]
Buhr et al.	Hg	105	80 – 2000	Pipe	↑	1967	[19, 20]
Horsten	Hg	84	400 – 1600	Pipe	↑	1971	[21]
Jackson et al.	Na	… 35	90 – 300	Pipe	↑↓	1994	[12]
Jacoby et al.	Hg	67	800 – 1400	Pipe	↑	1972	[22]
Johnston	Na	52	50 – 200	Pipe	↑↓	1986	[26, 27]
Kowalski et al.	Hg	67	2000	Pipe	↑	1974	[23]
Volchkov et al.	Na, NaK	55	3 – 150	Pipe, Annulus	↑	1969	[28]
Walton et al.	Na	… 35	90 – 260	Pipe	↑↓	1991	[11]
Wendling et al.	Na	6 – 30	5 – 185	Rectangular	↑	1971	[10]

Brukx et al. [18] (1976)

With the intention of investigating the flow in the inlet plenum of the SNR reactor Brukx et al [18] performed experiments. Thereby, a test section with two coaxial tubes was built, with the larger tube designed as a vessel. The smaller tube was placed in the center of the larger tube forming an annular space. Sodium was guided through the annular space in downward direction and redirected at the bottom to flow upward in the central pipe. The annular downward channel has a length of a 1500 mm with an outer annulus diameter of 594 mm. The central pipe has a length of 1410 mm and an internal diameter of 254 mm. The wall thickness of the central pipe is 8 mm. Hence, the inner annulus diameter is 270 mm. With these dimensions, the test section has a scale of 1:1 in axial and 1:6 in radial direction with respect to SNR dimensions. The central pipe of the test section has a L/d ratio less than 6, while measurements were taken at $L/d \approx 0; 2; 4; 6$. Due to the short length of the flow channel with respect to the pipe diameter undeveloped flow conditions must be assumed. This means that the heat transfer is higher as for developed flow. Hence, it is impossible to quantify the influence of mixed convection on the results due to the super positioning of different phenomena. Due to the countercurrent flow, no uniform heat flux or wall temperature is established. In total three scenarios are investigated with different mass flow rates and different temperature increases. Their data agree with the other data from a qualitative point of view. One of the main challenges for the evaluation of these data is the limited number of data points corresponding to a certain boundary condition. For the Brukx et al. [18] data 10 values for the Nusselt number as function of Z_1 are reported. These 10 data points are obtained at two different Péclet numbers, two different axial levels and in the central pipe and the annular space. Hence, qualitative and quantitative statements related to, say, a Péclet number dependency during mixed convection are difficult to make.

Buhr [19] (1967)

Buhr [19], and Buhr et al. [20] published heat transfer data for mercury and sodium-potassium flows. During the mercury experiments, the influence of buoyancy on the results has been identified. An empirical correlation is developed to identify if buoyancy has an influence on the turbulent flow, see Eq. (1). Applying this correlation to their own data, the velocity and temperature profile distortions of some experimental data could be reproduced. Only the data affected by buoyancy are replotted here. These data are in qualitative agreement to others (Horsten [21], Jacoby [22], Kowalski [23]) though rather large quantitative discrepancies are present. The test section used by Buhr [19] consists of a pipe with an internal diameter of 50 mm and a heated length of 4445 mm. With an inlet section of more than 80 hydraulic diameters developed flow can be assumed. The main drawback of these data is that for each Péclet number only one or two different Z_1 values are studied. Hence, these experimental data withdraw themselves from a comprehensive evaluation with respect to Péclet number dependencies.

Horsten [21] (1971)

The loop and test section used by Horsten [21] is identical to the one used by Buhr [19]. One of the main differences to the earlier investigations by Buhr [19] is the establishment of three Péclet number regimes ($Pe \approx 400$, 800 and 1400). For each Péclet number several Nusselt numbers with different Z_1 parameters are reported. This can allow an evaluation regarding the Péclet number dependency during mixed convection. They found out that the superposition of free convection on forced convection has a visible effect on the velocity profile until, at least, Reynolds numbers of 50000.

Huetz and Petit [24] (1974)

The experimental data of Huetz and Petit [24] are obtained in a horizontal annulus. Unfortunately, no information concerning the geometry is provided in their original paper. Hence, their data cannot be used for this study.

Jackson et al. [12] (1994)

Heat transfer to sodium under mixed convection in a vertical pipe is the subject of the Jackson et al. [12] experiment. Besides the mixed convection, the heat transfer in the entrance region of the pipe is studied as well. In addition, upward and downward flow are studied. The test section is a 2800 mm long with a heated length of 2400 mm. The internal pipe diameter is 67 mm. Nusselt numbers as a function of the dimensionless distance from the entrance are reported for Péclet numbers up to 300. One of the main differences to other publications is the use of the buoyancy parameter B instead of Z_1. For values of B of up to 0.13 experimental data are provided. The main finding of the experimental activities is the heat transfer enhancement at the entrance of the test section. The enhancement is decaying with increasing distance to the entrance. The trend of the decay is related to the intensity of the buoyancy, higher buoyancy = faster entrance effect decay. Heat transfer enhancement due to buoyancy-aided flows is more pronounced than for buoyancy-opposed flows. During the evaluation of the data it turned out that the provided plots for the forced convection heat transfer are not corresponding to the Nusselt number they used.

Jacoby [22] (1972)

Mercury is used in the experiment performed by Jacoby [22, 25]. The test section is a vertical circular pipe with an internal diameter of 36.42 mm. The inlet section has the length of 65 hydraulic diameters, thus allowing the full development of the velocity and temperature profiles. The heated section has a length of 67 hydraulic diameters. For two Reynolds numbers (~ 30000 and ~ 60000) Nusselt numbers are reported. Significant distortions in the velocity and temperature profiles are observed as a result of the influence of free convection on forced convection heat transfer. In addition, eddy diffusivity of heat and momentum confirmed the influence of free convection on the heat transfer. A clear Péclet number dependency is visible on the heat transfer impairment. With increasing Reynolds number, the relative Nusselt number decreases. At $Re \approx 30000$ ($Pe \approx 800$) the relative Nusselt number has a minimum at around 0.85, while at $Re \approx 60000$ ($Pe \approx 1400$) a minimum of 0.75 is reported.

Johnston [26] (1986)

The data of Johnston [26] and Jackson et al. [27] are related to heat transfer from a sodium-to-sodium heat exchanger. The heat exchanger consists of a horizontal concentric annulus with a pipe in the center. The heat exchanger has a length of 2100 mm. The central pipe has inner diameter of 42 mm and an outer diameter of 44.4 mm, while the concentric annulus has an internal diameter of 60 mm. Four different flow and heat transfer configurations are investigated: 1) buoyancy-opposed flow with heated downward flow in the pipe and cooled upward flow in the annulus. 2) buoyancy-opposed flow with a cooled upward flow in the pipe and heated downward flow in the annulus. 3) buoyancy-aided flow with heated upward flow in the pipe and cooled downward flow in the annulus. 4) buoyancy-aided flow with cooled downward flow in the pipe and heated upward flow in the annulus. During these conditions clear distinctions to pure forced convection are observed with increasing heat load. This resulted in enhanced heat transfer for buoyancy-aided flows and impaired heat transfer for buoyancy-opposed flows. One of the main drawbacks of their results is the rather large temperature variation in circumferential direction at the outer wall of the heat exchanger. The variations are in the range of 25 %. That has a large influence on the total heat transfer coefficient, which is reported for the whole heat exchanger. The variations increase with increasing buoyancy influence.

Kowalski [23] (1974)

This study is a repetition of the experiment performed by Jacoby [22]. The same loop is used with the same boundary conditions, except that the experimental campaign has been extended to higher Reynolds numbers. One of the subjects of the experiment of Kowalski [23] is to evaluate if at $Re \approx 90000$ the natural convection effects can be neglected. It turned out that the velocity and temperature profiles are not disturbed at $Re \approx 90000$ for small heat fluxes only. At larger heat fluxes, the distortions are clearly visible. It is interesting to note that even though differences in the results are obtained by Jacoby [22] and Kowalski [22] for the same parameter combination no statements on the differences are given by the later one.

Volchkov et al. [28] (1969)

The heat transfer to sodium and sodium-potassium alloy flowing vertically through short pipes is subject of the experiments performed by Volchkov et al. [28]. Thereby, the test section consisted of a central pipe and an annular space around the pipe. The flow in the pipe is upward, while the flow in the annular clearance was upward or downward. Three test sections are used with internal diameters of 68, 102 and 135 mm. The corresponding width of the annular space are: 6.0, 5.0 and 7.5 mm, respectively. The length of the heat transfer section is 5 hydraulic diameters each time. Their results show clearly a different qualitative trend compared to the other experimental data. Due to the short length of the heat transfer section and the short inlet section it is likely that the results are influenced by the entrance length effect. Due to the heat transfer enhancement at the vicinity of the flow channel entrance, it is expected that the result of Volchkov et al. [28] are higher than usual, as if only mixed convection is considered.

Walton et al. [11] (1991)

The experimental set-up of Walton et al. [11] is identical to Jackson et al. [12]. Actually, the same persons are involved in these two experimental studies. The only difference in the information provided is that Walton et al. [11] present the data in terms of heat transfer coefficients, while in Jackson et al. [12] data are given for Nusselt numbers.

Wendling et al. [10] (1971)

Heat transfer under mixed convection in vertical rectangular channels are investigated by Wendling et al. [10]. Thereby, different channel widths are studied, ranging from 34 to 164 mm. The rectangular test section is 3000 mm in length, while the heated section is the upper 2000 mm. The applied Péclet number ranges from 5 to 185. The presented results for the Nusselt number as function of Gr^*/Re are consistent to each other. Only very small deviations exist. One of the major findings is that the heat transfer coefficient decreased with increasing velocity at low Péclet numbers ($Pe < 200$).

4. EVALUATION

All the available and extractable experimental data points are gathered in one graph (Figure 2), where the Nusselt number is plotted as function of Z_1 (see Eq. 1). On the first impression, a general linear relation might exist between Nusselt number and Z_1. On a second look several deviations are visible. First of all, at smaller Z1 numbers the data are spread over a larger Nusselt number range. These data originate from heavy liquid metals flows and larger Péclet numbers. A second large deviation is visible for the Volchkov et al. [28] experiments. As mentioned above these experiments were carried out in a test section of short length, meaning that it is most likely that the heat transfer is influenced by the entrance length effect. Hence, it is not possible to identify the cause of the higher than average Nusselt numbers.

Similarly, the experiments of Jackson et al. [12] and Walton et al. [11] are performed, intentionally, under the influence of the entrance length effect. Due to the richness of available data, a dedicated investigation of these experiments was performed, with the aim to develop a combined entrance length and mixed convection model for vertically upward sodium flows [29].

The general consensus of the evaluation of these experiments is, for some experiments, the incomplete provision of relevant data. Information concerning, among others, measurement errors and data analysis are rather sparse. With respect to reproducibility some references lack information like the consistent provision of data according to Nu = f(Z_1, Pe, x/d). Nevertheless, all these experiments are a useful source for the purpose of this study. The following list is an overview on the evaluation:

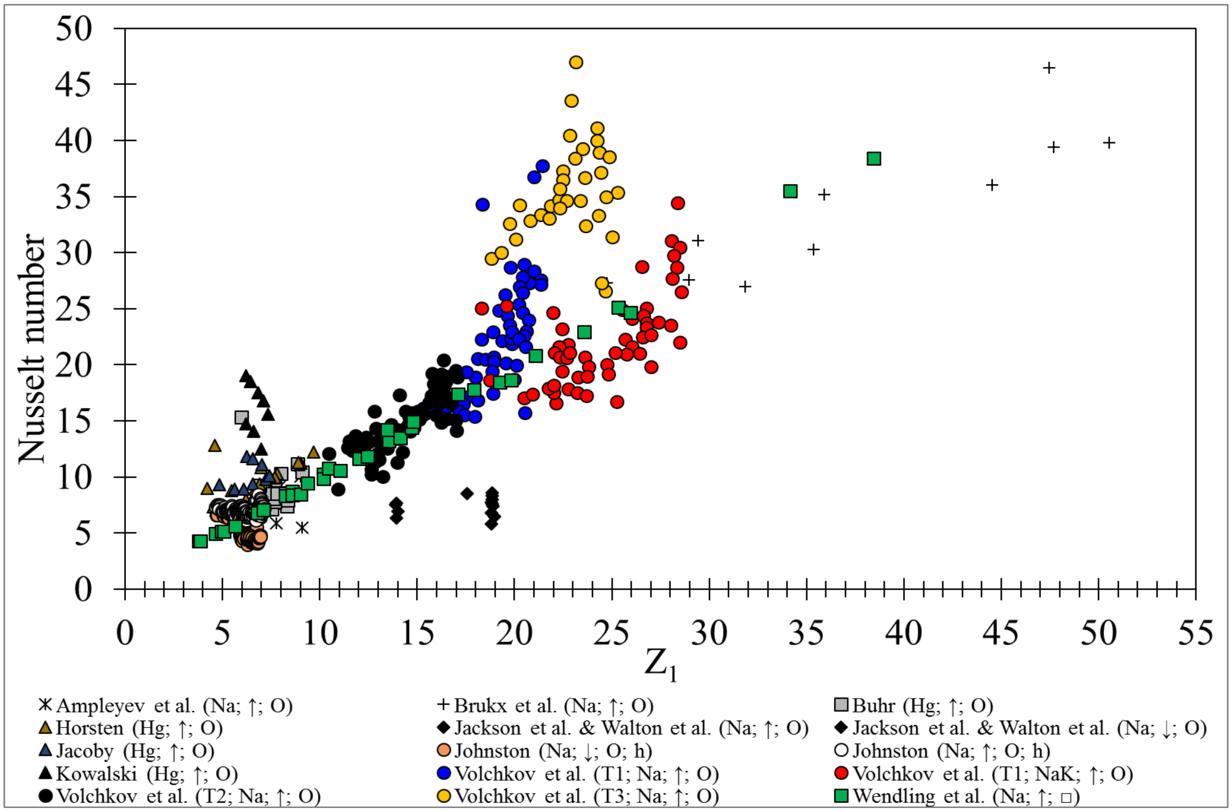

Figure 2. Overview of experimental data for mixed convection heat transfer with liquid metals.

- Buoyancy influences the temperature and velocity field.
- For buoyancy-aided flows, heat transfer enhancement is visible.
- For buoyancy-opposed flow heat transfer impairment is visible.
- Heat transfer under the influence of free convection differs considerably from pure forced convection.
- Most of the experiments have been performed in the 1960s and 1970s.
- The influence of the Péclet number is negligible for low Péclet numbers ($Pe < 50$).
- An influence of the Péclet number is visible for higher Péclet numbers ($Pe > 100$).
- Almost all experiments have some inconsistencies and minor flaws in common (see list below).
- No general valid statements can be given for the available experimental data.

The second list following below is a compilation of flaws and inconsistencies found in the original references of the available experiments:

- **Incorrect manuscripts:** At one point in the paper of Ampleyev et al. [17] Z is expressed as $Z = \sqrt{\ldots}$, while at another position $Z = 4\sqrt{\ldots}$ Such inconsistencies or mistakes make the evaluation of the experiment time consuming and difficult.
- **Different nomenclature:** In, e.g., Buhr [19], Jackson et al. [12] the Grashof number Gr is defined as a function of the radial temperature difference ($T_{wall} - T_{bulk}$), while the modified Grashof number Gr* is a function of the axial temperature difference ($T_{outlet} - T_{inlet}$). In Cotton et al. [6] and Horsten [21] it is the other way around, $Gr = f(T_{outlet} - T_{inlet})$, while $Gr^* = f(T_{wall} - T_{bulk})$.
- **Combination of phenomena:** In some experiments (Volchkov et al. [28], Brukx et al [18]) short test sections are used with a length-to-diameter-ratio (*l/d*) of less than 10. This means that mixed convection and the entrance length effect have an influence on the heat transfer. The experiments of Jackson et al [12] and Walton et al [11] suggest that with increasing influence of buoyancy, the influence of the entrance length effect decreases. Thereby, the entrance length effect vanishes for $x/d < 10$. Hence, it might be also possible that the short length of the test sections of Volchkov et al. [28] and Brukx et al. [18] may not influence the results. Nevertheless, with the limited number of experimental points it is not possible to make a quantitative statement which phenomenon has which effect on the results.
- **Measurement approach:** During mixed convection the Nusselt number is a function of the Péclet number and a buoyancy related parameter (Z_1 or B). Hence, $Nu = f(Pe, Z_1)$. To provide useful data one should perform experiments in a way that one parameter, say Pe, is fixed, while the other is varied. This should be continued till a consistent Pe over Z_1 matrix exists. Only Horsten [21], Jacoby [22], Kowalski [23] and provide, at least roughly, such a matrix.
- **Missing information:** To calculate Gr and Gr* the radial and axial temperature differences are needed. In some cases, these are not provided [17, 28]. Furthermore, in some experiments [10] only Nusselt number as a function of Z_1 is provided. The corresponding Péclet numbers are not reported. Hence, the post-test calculation is limited and therefore incomplete.
- **Reproducibility:** Jacoby [22] and Kowalski [23] performed experiments at the same loop with identical boundary conditions but with different qualitative results. No information is provided on why such differences occur. Due to the complexity of experiments in liquid metals many reasons might play a role. One of them could be the aging issue. With time, the wetting performance of the heavy liquid metal changes and also deposits on the wall might additionally increase the contact resistance. This results in reduced heat transfer capabilities.

Based on the above given statements, it is impossible to develop one model, which includes the present effects of all experiments. In some cases, the mixed convection heat transfer interferes with heat transfer effects caused by, e.g., the inlet section to cause the flow to be undeveloped. Furthermore, some experiments do not provide sufficient information and others are related to quadratic channels. Hence, only for a dedicated scenario a model can be developed. In the present case, the focus is now on mixed convection with mercury flow, including the experiments Buhr [19], Horsten [21], Jacoby [22] and Kowalski [23].

The experimental data points are plotted, for the sake of clarity, in several charts, see Figure 3. Some of the data are omitted from the charts for an illustrative representation. The Nusselt number and the relative Nusselt number (local Nusselt number divided by the Nusselt number for forced convection at the corresponding Péclet number) are plotted as functions of Gr*, B, Z_1 and Z_2.

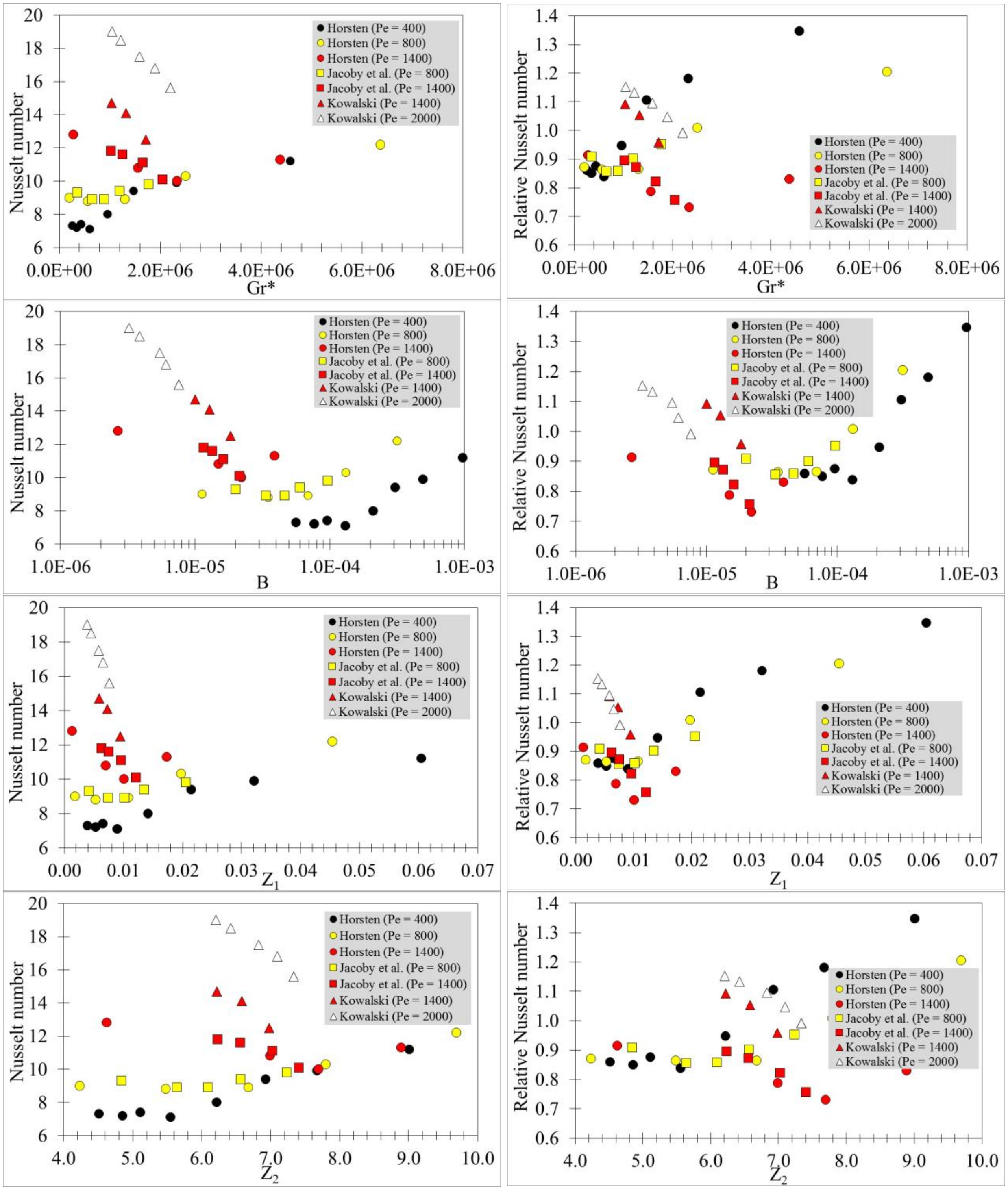

Figure 3. Nusselt number (left side) and relative Nusselt number (right side) as a function of G*, B, Z_1 and Z_2 for the experiments with Mercury.

The first thing to notice is that for the Nusselt number plots a clear distinction between the different Péclet numbers is possible. For the relative Nusselt number the difference between varying Péclet numbers are blurred. In addition, the depiction in Nusselt numbers shows a kind of limiting value. Below a certain G*, Z_1 parameter the Péclet number difference are clearly visible, while above a certain threshold all experimental cases behave identically and no Péclet number dependency seems to exist. The authors are aware that the experimental data points in that regions are sparse, but nevertheless a starting point for the data evaluation is set.

Based on the above given diagrams, the representation of Nusselt number as a function of the modified Grashof number (Gr*) seems to be the most promising one for the derivation of general statements. The experimental data along with the proposed model result are shown in Figure 4. As mentioned above, a threshold for the Péclet number dependency exist.

For the modified Grashof number (Gr*), the value is around $4 \cdot 10^6$. For Z_1 the threshold is at around 0.025, while for Z_2 the threshold is at around 9.0. Above those values, no Péclet number dependency is visible. The calculated values are based on polynomial interpolations scheme of the experimental data. The result is a look-up table (see Table II), which is valid for mercury flow, Péclet numbers between 100 and 2000, and modified Grashof numbers up to $1 \cdot 10^7$.

5. CONCLUSION

The aim of this paper is to gather relevant experimental data related to liquid metal heat transfer under mixed convection. Several experiments are found and presented. In principle, all experiments are consistent and the results are comparable to each other. One of the main challenges related to mixed convection is, besides the underlying physics, the different way of presenting the results. Several dimensionless numbers exist to express or to show that mixed convection is present (Gr, Gr*, Z_1, Z_2, B). This complicates the process of empirical model development. In addition, some publications lack necessary information to simulate them (Nu = f(Pe, Gr*, etc.). Furthermore, in some experiments other effects are superimposed to the mixed convection heat transfer (entrance length effect).

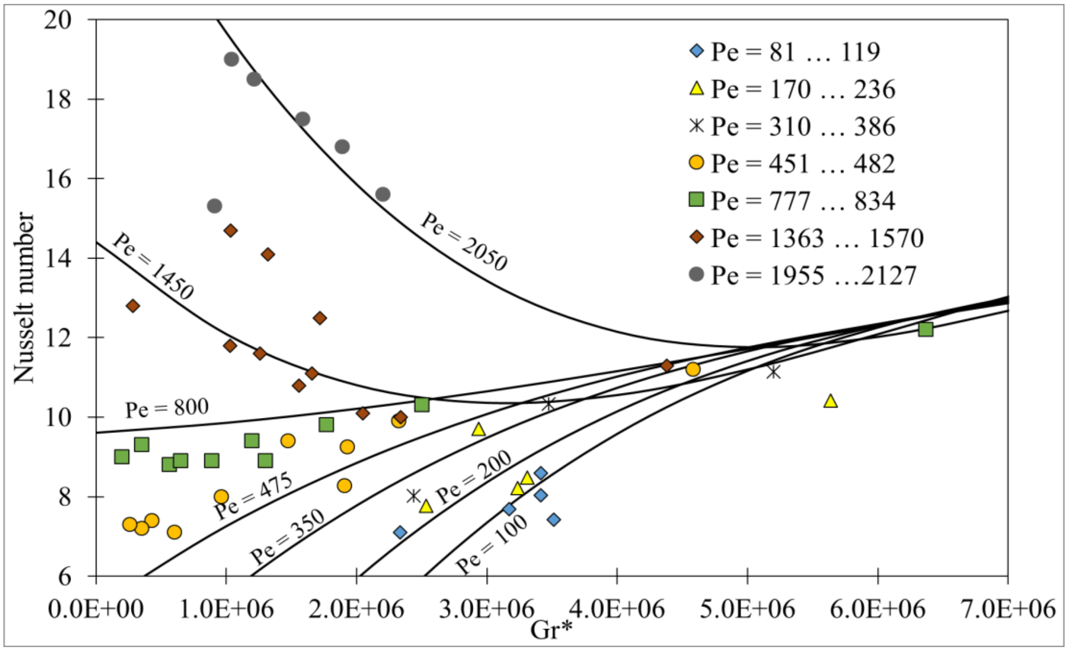

Figure 4. Nusselt number as a function of Gr* for the experimental and calculated data.

Table II. Look-up table for the Nusselt number as function of the Péclet and modified Grashof number for mixed convection heat transfer with mercury flow

Gr*	Pe									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
0.E+00	0.00	0.53	1.96	3.68	5.44	7.08	8.52	9.70	10.64	11.38
1.E+06	0.34	2.72	4.69	6.28	7.55	8.54	9.29	9.86	10.28	10.60
2.E+06	4.32	5.94	7.24	8.26	9.03	9.58	9.97	10.21	10.35	10.41
3.E+06	7.35	8.37	9.16	9.75	10.18	10.45	10.60	10.65	10.63	10.56
4.E+06	9.58	10.15	10.57	10.87	11.07	11.17	11.19	11.16	11.08	10.97
5.E+06	11.17	11.41	11.59	11.71	11.77	11.79	11.77	11.72	11.64	11.56
6.E+06	12.26	12.30	12.33	12.35	12.35	12.34	12.33	12.31	12.28	12.25
7.E+06	13.00	12.94	12.91	12.88	12.88	12.88	12.89	12.92	12.94	12.97
8.E+06	13.55	13.48	13.43	13.41	13.42	13.44	13.47	13.52	13.57	13.63
9.E+06	14.06	14.04	14.03	14.03	14.04	14.05	14.08	14.10	14.13	14.17
	1100	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**
0.E+00	11.97	12.51	13.10	13.81	14.74	15.94	17.45	19.27	21.34	23.55
1.E+06	10.87	11.14	11.45	11.84	12.37	13.07	14.00	15.20	16.71	18.58
2.E+06	10.45	10.48	10.56	10.70	10.95	11.35	11.92	12.71	13.75	15.07
3.E+06	10.48	10.39	10.34	10.34	10.42	10.61	10.92	11.40	12.05	12.91
4.E+06	10.85	10.73	10.64	10.58	10.57	10.62	10.76	11.00	11.36	11.85
5.E+06	11.47	11.37	11.29	11.23	11.19	11.18	11.21	11.29	11.43	11.63
6.E+06	12.21	12.18	12.14	12.11	12.08	12.05	12.03	12.01	12.01	12.01
7.E+06	12.99	13.01	13.03	13.03	13.03	13.01	12.97	12.92	12.84	12.74
8.E+06	13.69	13.74	13.78	13.82	13.83	13.83	13.81	13.75	13.67	13.55
9.E+06	14.20	14.23	14.25	14.28	14.29	14.30	14.29	14.28	14.25	14.21

Hence, only a limited number of the presented experiments are suitable for the development of empirical models. The presented model is therefore only applicable to mercury flows. Nevertheless, a consistent and reproducible trend is visible for these experiments.

Even if no generally applicable model can be developed, based on the available experiments, the presented results give an overview on mixed convection heat transfer for liquid metals. By any chance, this paper might trigger a discussion on future activities related to mixed convection. In principle, the experimental database is sparse and incomplete. Hence, the development of applicable models for best-estimate system codes, but also for CFD codes is very difficult to almost impossible.

Therefore, new and comprehensive experiments are necessary, focusing on the investigation of a Péclet number range instead of one particular Péclet number. Furthermore, the transition from forced to mixed convection should be experimentally investigated as well. This would allow a development of models for the prediction of mixed convection heat transfer general applicability.

NOMENCLATURE

c_p	Specific heat
d	Diameter
g	Acceleration of gravity
k	Thermal conductivity
l	Length

q	Heat flux
T	Temperature
x	Distance from inlet
β	Thermal expansion coefficient
η	Dynamic viscosity
ρ	Density

B	Buoyancy parameter according to [11, 12]
Gr	Grashof number
Gr*	Modified Grashof number
Nu	Nusselt number
Ra	Raleigh number
Ri	Richardson number
Z_1	Buoyancy parameter according to [9]
Z_2	Buoyancy parameter according to [10]

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