Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Wissenschaftliche Berichte
FZKA 7352

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Oktober 2007

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2007

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Mitglied der Hermann von Helmholtz-Gemeinschaft
Deutscher Forschungszentren (HGF)

ISSN 0947-8620

urn:nbn:de:0005-073522

Bewertung von Korrelationen für den Wärmeübergang in Schwermetall gekühlten Reaktorkernen

Zusammenfassung:

In der Entwicklung der Beschleuniger getriebenen Systeme XT-ADS und EFIT sind Blei - Wismut - Eutektikum (LBE) und Blei als Kühlmittel vorgesehen. Zur Berechnung des Wärmeübergangs von der Brennstaboberfläche zum Kühlmittel sind Korrelationen erforderlich. Es wird ein Überblick über existierende Korrelationen für hexagonale und quadratische Brennstabanordnungen in Bezug auf ihre experimentelle Validierung gegeben. Auswirkungen auf den Wärmeübergang bei Reaktoranwendungen, die aufgrund veränderter Randbedingungen die Korrelationen verändern könnten, werden angesprochen. Dies ist der Einfluss von Abstandshaltern und Auswirkungen des axialen Leistungsprofils.

Abstract:

In the development of the accelerator driven systems XT-ADS and EFIT lead-bismuth eutectic alloy (LBE) and lead are foreseen as coolant respectively. For calculation of the heat transfer from the fuel rod surfaces to the coolant correlations are necessary. Existing correlations for triangular and square fuel pin arrangements are reviewed with respect to their experimental qualification. Effects on the heat transfer in reactor application are addressed, which could alter the correlations due to deviating boundary conditions. These are the influence of spacers and consequences due to the axial power profile.

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1 Introduction

In the development of the accelerator driven systems XT-ADS and EFIT lead-bismuth eutectic alloy (LBE) and lead are foreseen as coolant respectively. In the thermal-hydraulic characterization of sodium cooled reactors the choice of correlations used to calculate the heat transfer from the fuel rods to the coolant has not had a similarly high priority, because the temperature difference between coolant and clad outer surface normally does not exceed 10 to 15 K and thus inaccuracies wouldn't be of high importance in respect to other uncertainties of the calculation. Due to the lower thermal conductivity of LBE and lead compared to sodium this temperature difference increases to several 10 K, putting higher priority to the choice of an appropriate correlation, not only because of its influence on the fuel temperatures but also in view of the temperature sensitive thermal-mechanical and chemical properties of the clad material.

2 Review on the development of correlations

2.1 Correlations for tube flow

In the middle of the last century, the development of correlations for the heat transfer of low Prandtl number fluids (e.g. liquid metals) started with a theoretical evaluation of flows within tubes. R. N. Lyon showed in his PhD thesis [1] that the theoretical results for calculation of the Nusselt number can be approximated by a function of the form

$$\mathrm{Nu} = a + b \cdot \mathrm{Pe}^{c} \quad (1)$$

Pe (Péclet number) = Pr (Prandtl number) ∗ Re (Reynolds number)

where "a" denotes the molecular conduction term which is dependent on the heating boundary and flow conditions and the second term describes the eddy diffusivity contributions. The function, known as the Lyon correlation, was proposed:

$$\mathrm{Nu} = 7.0 + 0.025\mathrm{Pe}^{0.8} \quad (2)$$

On this basis, R. A. Seban and T. T. Shimazaki [2] published in 1951 for turbulent tube flow with constant wall temperatures the correlation

$$\mathrm{Nu} = 5.0 + 0.025\mathrm{Pe}^{0.8} \quad (3)$$

The same function was found by V. I. Subbotin et al. [3] to describe their measurements of carefully cleaned sodium flowing in circular tubes in the range of Péclet numbers from 40 to 1150 with an accuracy of 10%. V. I. Subbotin and others from the same institute (Physics and Power Institute (IPPE), Obninsk) published later on (see section 2.2) different correlations developed for "longitudinally wetted tube bundles" [4] and [12].So the quotation of "Subbotin correlation" can be misleading if the respective application (tube or bundle) or the state of experimental qualification is not respected.

Recently X. Cheng and N. Tak [5] published a detailed review on correlations for liquid metals flowing in tubes that lead to the recommendation of a correlation giving lower values than eq. (3).

2.2 Correlations for flow in triangular rod bundles

On basis of the work R. N. Lyon has performed for tube flows A. J. Friedland and C. F. Bonilla calculated Nusselt numbers for parallel liquid metal flow trough infinite tube bundles [6]. They found that the results could be approximated by a function according to equation (1) where both terms on the right hand side are dependent from the pitch-to-diameter ratio (P/D). In the correlation they proposed (eq. 4) the Péclet number is corrected by a factor called Ψ, which is the ratio of the eddy diffusivity of heat (ε_H) and the eddy diffusivity of momentum (ε_M). The function had been evaluated in the range 10 ≤ Pe ≤ 100000 and 1.375 ≤ P/D ≤ 10.

$$Nu = 7.0 + 3.8\left(\frac{P}{D}\right)^{1.52} + 0.027\left(\frac{P}{D}\right)^{0.27}(\Psi \cdot Pe)^{0.8} \tag{4}$$

In the early sixties of the last century, experimental investigations have been performed in the Brookhaven National Laboratories measuring the heat transfer in a 13 pin bundle cooled with mercury [7] and in a 19 pin bundle cooled with a sodium potassium alloy (NaK) [8]. Both campaigns used a P/D of 1.75. The respective theoretical considerations used semi-empirical correlations in the form of function (4), semi-empirical because the P/D dependence followed theoretical evaluations:

$$Nu = 6.66 + 3.126\frac{P}{D} + 1.184\left(\frac{P}{D}\right)^{2} + 0.0155(\Psi \cdot Pe)^{0.86} \tag{5}$$

The factor Ψ can be approximated by the empirical equation

$$\Psi = 1 - \frac{1.82}{Pr \cdot \left(\frac{\varepsilon_M}{\nu}\right)_{max}^{1.4}} \tag{5a}$$

For the calculation of $(\varepsilon_M/\nu)_{max}$ an approximation can be used [9]:

$$\ln\left(\frac{\varepsilon_M}{\nu}\right)_{max} = 0.864 \cdot \ln(Re) - 0.24\frac{P}{D} - 2.12 \tag{5b}$$

In the respective reference [9] the logarithm is written “lg” suggesting that the logarithm to the basis 10 should be used, but evaluating the function in this way yields unreasonable results.

In parallel to the experiments performed in the USA, experiments in longitudinally wetting pin bundles have been performed at different locations in Russia. In 1969 Borishanskii et al. [10] published results obtained in 7 pin arrangements with $1.1 \le P/D \le 1.5$ using coolants with Prandtl numbers of ≈ 0.007 (sodium) and ≈ 0.03 (mercury). The correlation used to describe the established database, which had been extended by measurements of the IPPE (Prandtl number of 0.024), was selected to match theoretical predictions for $Pe \ge 1000$ and predicted values for laminar flow for $Pe \le 200$:

$$Nu_{lam} = 24.12\log_{10}\left(-8.12 + 12.76\frac{P}{D} - 3.65\left(\frac{P}{D}\right)^{2}\right)$$

$$Nu_{turb} = 0.0174\left(1.0 - e^{-6.0\left(\frac{P}{D}-1.0\right)}\right)(Pe - 2000)^{0.9}$$

$$Nu = Nu_{lam} \qquad Pe \le 200$$

$$Nu = Nu_{lam} + Nu_{turb} \qquad 200 \le Pe \le 2200 \tag{6}$$

The experimentally qualified range for the P/D ratio is $1.1 \le P/D \le 1.5$.

In France at the Comissariat à l'Énergie Atomique (Saclay and Fontenay-aux-Roses) an experimental programme had been performed between 1961 and 1969 investigating 31 pin bundles cooled by NaK both using arrangements with heater pins and heat exchanger tubes. The applied P/D ratios were 1.25, 1.6, and 1.95. In 1972, H. Gräber and M. Rieger (EURATOM Ispra) published the final analysis of these experiments [11]. The correlation they propose is quoted to describe also other results published at that time [7], [8], [10]):

$$\mathrm{Nu} = 0.25 + 6.2\frac{P}{D} + \left(-0.007 + 0.032\frac{P}{D}\right)\mathrm{Pe}^{\left(0.8 - 0.024\frac{P}{D}\right)} \qquad (7)$$

Validity range: 150 ≤ Pe ≤ 4000, 1.2 ≤ P/D ≤ 2.0

Experimental and analytical research on heat transfer in fuel elements at the IPPE Obninsk down to P/D ratios of 1.0 led to the recommendation of a rather complicated correlation in 1973, covering a wide spectrum of the parameters and quoting an accuracy of ±15 %. It had been presented by V. I. Subbotin, et al. at a conference in Obninsk in 1973 [12]. Unfortunately it was impossible to get access to the respective reference, but in a paper by P. A. Ushakov (co-author of ref. [12]) et al. published in 1977 the respective correlation is discussed [13]:

$$\mathrm{Nu}_{lam} = \left(7.55\frac{P}{D} - 6.3\left(\frac{P}{D}\right)^{-17\frac{P}{D}\left(\frac{P}{D}-0.81\right)}\right)\left(1 - \frac{3.6\frac{P}{D}}{\left(\frac{P}{D}\right)^{20}\left(1+2.5\varepsilon^{0.86}\right)+3.2}\right)$$

$$\mathrm{Nu} = \mathrm{Nu}_{lam} + \frac{3.67}{90\left(\frac{P}{D}\right)^{2}}\left(1 - \frac{1}{\frac{1}{6}\left(\left(\frac{P}{D}\right)^{30}-1\right)+\sqrt{1.15+1.24\varepsilon}}\right)\mathrm{Pe}^{0.56+0.19\frac{P}{D}-0.1\left(\frac{P}{D}\right)^{-80}} \qquad (8)$$

Validity range: 1 < Pe < 4000, 1.0 ≤ P/D ≤ 2.0, 0.01 < ε < ∞

The parameter ε is called "approximate criterion of thermal similarity of the fuel rods". It is dependent on the geometry of the rods (number and geometry of claddings), the geometrical arrangement (triangular, square), and the thermal conductivities of the fuel rod, the claddings, and the coolant [14]. For triangular rod arrangements ε is subscripted with "6" (six neighbouring pins) and for square arrangements the subscript is "4" (four neighbouring pins). It is difficult to understand why the Nusselt number should depend on geometrical and thermal data of the fuel and the fuel to clad gap if it is used in the computer codes to calculate the heat transfer between the clad outer surface and the coolant. Therefore, it is recommended to use the equation for "fuel without cladding", i.e. ε is independent from the fuel rod arrangement and is the ratio of the thermal conductivities of the coolant and the cladding.

For increasing (P/D), the parameter ε looses more and more influence on the result of eq. (8) and for (P/D) ≥ 1.2, the simplification of eq. (8) to eq. (8a) has a deviation to eq. (8) of less than ± 5%:

$$\mathrm{Nu} = 7.55\frac{P}{D} - 20\left(\frac{P}{D}\right)^{-13} + \frac{3.67}{90\left(\frac{P}{D}\right)^{2}}\mathrm{Pe}^{\left(0.56+0.19\frac{P}{D}\right)} \tag{8a}$$

Validity range: 1 < Pe < 4000, 1.2 ≤ P/D ≤ 2.0

M. S. Kazimi and M. D. Carelli recommended a correlation which has been developed using several experimental campaigns conducted with the coolants Na, Hg and NaK [15]. According to A. E. Waltar [16] this correlation has been used for the FFTF analysis and in the CRBR analysis for the P/D ratios of 1.2 and 1.3:

$$\mathrm{Nu} = 4 + 0.16\left(\frac{P}{D}\right)^{5} + 0.33\left(\frac{P}{D}\right)^{3.8}\left(\frac{\mathrm{Pe}}{100}\right)^{0.86} \tag{9}$$

Validity range: 10 ≤ Pe ≤ 5000, 1.1 ≤ P/D ≤ 1.4

The “BREST report” [17] recommends for triangular arrays a correlation which is a combination of two different equations. The laminar part is taken from eq. (14) which has been developed for square arrays (see paragraph 2.3), the turbulent part from eq. (8a):

$$\mathrm{Nu} = 7.55\frac{P}{D} - 14\left(\frac{P}{D}\right)^{-5} + \frac{0.041}{\left(\frac{P}{D}\right)^{2}}\mathrm{Pe}^{\left(0.56+0.19\frac{P}{D}\right)} \tag{10}$$

A validity range is not given.

For this correlation neither a reference nor an experimental qualification is given. It looks rather like a “conservative” approach, when compared to eq. (8a), giving for a fixed P/D a constant reduction of the Nusselt number.

Recently K. Mikityuk reviewed four sets of experimental data obtained in bundle geometry [18], the data being those of Maresca and Dwyer [7], Borishanskii et al. [10], Gräber and Rieger [11] and Zhukov et al. [22]. For the inclusion of the data of Zhukov et al., where a square bundle geometry was used, it is argued that these data are within the scatter band of the others. A correlation was derived which gives the best fit to the in total 658 experimental data points:

$$\mathrm{Nu} = 0.047\left(1 - e^{-3.8\left(\frac{P}{D}-1\right)}\right)\left(\mathrm{Pe}^{0.77} + 250\right) \tag{11}$$

Validity range: $30 \leq Pe \leq 5000$, $1.1 \leq P/D \leq 1.95$

In Fig. 1 different correlations are evaluated for the actually foreseen P/D ratio of the XT-ADS design (1.409), the shaded area marks the Péclet number range for the steady state coolant flow velocity of 1.6 m/s. The same correlations are shown in Fig. 2 for the 3-zone-core draft of EFIT applying the P/D ratio 1.563, which holds for the zones I and II. Zone III with P/D=1.422 is very near to the value of XT-ADS shown in Fig. 1. In order to highlight the error that could be made, when using an inappropriate condition, the correlation of Seban/Subbotin (eq. (3)) for clean tubes is included.

Both figures show that the correlations of Borishanskii (eq. (6)), Gräber (eq. (7)), Subbotin/Ushakov (eq. (8a)), and Mikityuk (eq. (11)) are relatively close together. The semi-empirical correlation of Dwyer (eq. (5)) provides results larger than the four correlations mentioned above almost over the whole Péclet number range. Evaluating the correlations for P/D=1.75, where eq. (5) is experimentally qualified, gives a better agreement of eq. (5) with eqs (6), (7), (8a) and (11), especially in the higher Péclet number range. The correlation of Kazimi (eq. (9)) is already in Fig. 1 applied slightly beyond its validity range and gives there considerably lower Nusselt numbers than the other correlations, whereas for P/D=1.563 in Fig. 2 the steepness of the gradient is much higher. The low values are consistent with a remark in [19] where eq. (9) is recommended because it "consistently yields the most conservative values of the heat transfer coefficient". The correlation of Borishanskii (eq. (6)) is the only one which follows the theoretical findings that in the laminar region the heat transfer coefficient should be constant. Despite his own measurements where he didn't find clearly this behavior, he adopted this formulation, (in the low Péclet number range the experimental results are scattering very much, what is common to many experimental campaigns). The correlation of Mikityuk (eq. (11)) fits the data used for qualification best, but eqs. (8) and (8a) respectively are fitted to a data base which is extended by additional data from the IPPE. This could be the reason why in the report of Mikityuk [18] eq. (8a) is recommended to be used in the TRAC/AAA calculations for the ELSY lead cooled reactor. The most important difference between the eqs of Gräber (eq. (7)) and Subbotin/Ushakov (eq. (8a)) is in the low Péclet number range which is important for the analysis of loss of flow accidents. Especially for the experiments with heated rods considered in the report of Gräber [11] the proposed correlation eq. (7) partially underestimates the measurements below Péclet numbers of 500 to 700.

In summary it can be stated that the correlation of Subbotin/Ushakov (eq. (8a)) looks to be the one with the best experimental qualification when applied to P/D ratios between 1.2 and 2. For application with a P/D ratio below 1.2 the extended formulation of eq. (8) should be used.

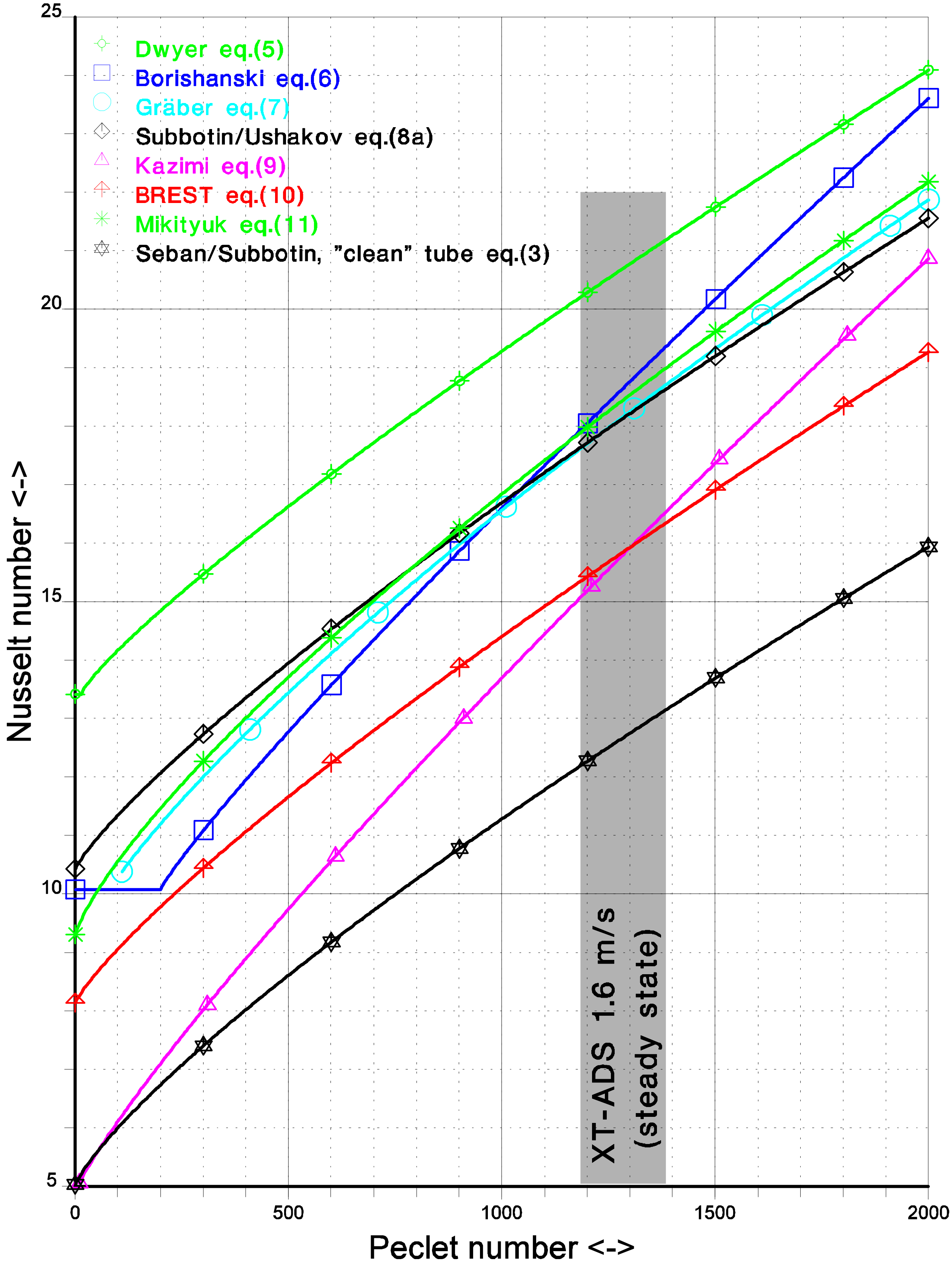

Fig. 1: Correlations for the heat transfer in triangular arrays at P/D = 1.409

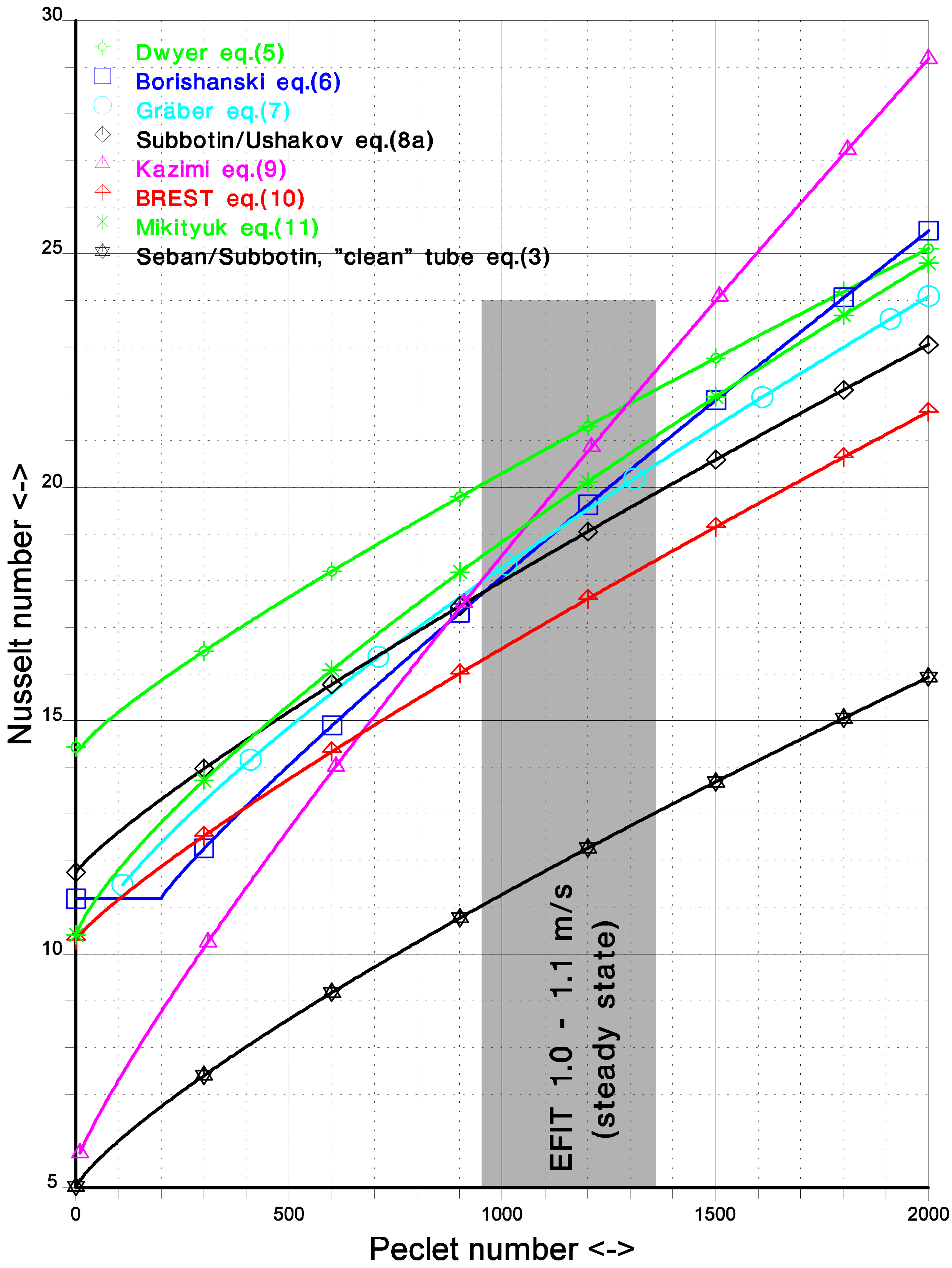

Fig. 2: Correlations for the heat transfer in triangular arrays at P/D = 1.563

2.3 Correlations for flow in square rod bundles

Using the principal of equivalent flow area per pin in triangular (hexagonal) and square rod bundle arrangements A. J. Friedland [6] derived the dependency

$$\frac{P_{tr}}{D} = \sqrt{\frac{2}{\sqrt{3}}}\left(\frac{P_{sq}}{D}\right) \approx 1.075\left(\frac{P_{sq}}{D}\right) \tag{12}$$

Postulating equivalent hydraulic diameters in the respective sub-channels gives the same relation, but whether these conditions are necessary or even sufficient for equivalent heat transfer behaviour has not been shown. Eq. (12) applied to the correlations given in paragraph 2.2 would give for the same P/D-ratio in square rod bundles higher Nusselt numbers than in triangular rod bundles, because the correlations give increased values for rising P/D-ratios.

X. Cheng and N. I. Tak performed a computational fluid dynamic analysis (CFD) with CFX on the thermal-hydraulic behaviour in sub-channels of fuel elements with triangular and square fuel rod arrangements [20]. In Fig. 17 of the respective report, displayed in Fig. 3, local Nusselt numbers in square and triangular arrangements at Pe = 1430 are compared. Θ = 0° is in the direction to the neighbouring pin, Θ = 30°, and Θ = 45° respectively, is in the middle of two neighbouring pins. (In the caption of the figure it should read for the curve marked with the pink square "Θ = 45°"). The azimuthal variations of the Nusselt number are more pronounced for the square rod arrangement, and taking the average of the values at Θ = 0° and Θ = 30° or 45° respectively as measure for the averaged Nusselt number along the perimeter it shows, that this averaged Nusselt number is in the range P/D = 1.3 to P/D = 1.8 for the square rod arrangement about 1.6 to 8.0 % lower than in the triangular rod arrangement. This decrease is not very significant and the authors of ref. [20] state, "A good agreement of the overall Nusselt number averaged over the entire rod surface can be observed between both lattice configurations", but the tendency of this analysis is in the opposite direction than given by eq. (12).

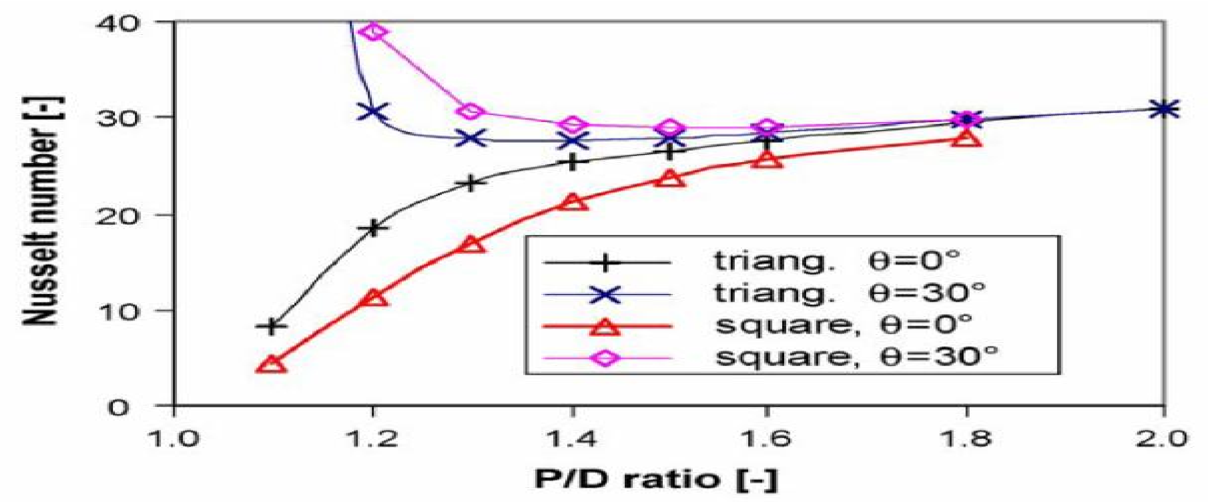

Fig. 3: Comparison of local Nusselt number in different lattices Pe = 1430 [20]

The “BREST report” [17] recommends also for square arrays a correlation which looks like a transcription of eq. (10) for triangular arrays with eq. (12), but the first summand is kept constant, the second summand is transformed using the reciprocal according to eq. (12) and only the residual parts are transformed with eq. (12). Thus, the resulting function gives lower Nusselt numbers than eq. (10), the respective function for triangular rod bundles.

$$Nu = 7.55\frac{P}{D} - 20\left(\frac{P}{D}\right)^{-5} + \frac{0.0354}{\left(\frac{P}{D}\right)^{2}} Pe^{\left(0.56+0.204\frac{P}{D}\right)} \quad (13)$$

It is quoted that this equation has been proposed in [21] and verified for (P/D) ratios of 1.28 and 1.46 in the range 100 < Pe < 1600, but this could not be found in the respective reference. Another study dealing with the BREST-OD-300 reactor by V. P. Smirnov et al. [23] recommends for the thermal-hydraulic calculation eqs. (14), (14a), and (14b).

The only available experimental investigation in square rod bundles has been performed in Russia using a 25-pin rod bundle cooled by NaK. Results for P/D ratios of 1.28 (7 data points) and 1.46 (13 data points) have been presented 1994 by A. V. Zhukov et al. in Pittsburgh [21]. A more detailed report has been published in 2002 [22], including results for P/D ratios of 1.25 (8 data points) and 1.34 (8 data points), and investigations on the influence of a spacer grid with obstruction of the flow cross section (ε_g) by 10 % (15 data points) and 20 % (11 data points) respectively. The experiments with spacer grid have been performed with P/D = 1.46. The proposed correlations to describe these results are:

$$Nu = 7.55\frac{P}{D} - 14\left(\frac{P}{D}\right)^{-5} + A \cdot Pe^{\left(0.64+0.246\frac{P}{D}\right)}$$

with	A = 0.007	for smooth rods (no spacers),	(14)
	A = 0.009	for spacer ε_g = 20 %	(14a)
	A = 0.010	for spacer ε_g = 10 %	(14b)

The validity range for eq. (14) is given with 10 ≤ Pe ≤ 2500 and 1.2 ≤ P/D ≤ 1.5, but the experimentally covered range is only 60 ≤ Pe ≤ 2000 and 1.25 ≤ P/D ≤ 1.46. Keeping in mind the limited database of in total 36 data for eq. (14) extensions beyond this range should be done cautiously.

In Fig. 4, the three equations of Zhukov eqs (14), (14a) and (14b) and eq. (13) given in the BREST report are compared for the P/D ratio of 1.46. Additionally the recommended correlation for triangular rod arrangements of Subbotin/Ushakov (eq. (8a)) is included, because according to Cheng et al. [5] and Mikityuk [18] the characteristics of the heat transfer in the two different bundle arrangements do not differ significantly. Eq. (11), developed including the data of Zhukov for square arrays, is also added. In Fig. 5, the same correlations are given for the P/D ratio of 1.34. Since no actual reactor design with square fuel rod arrangement is available, the P/D ratios have been selected to match ratios investigated experimentally [22].

For P/D = 1.46 eq. (8a) and (11) give results which are not fully apart from those of eq. (14), which has been adjusted to the experimental data. The deviation of the Nusselt numbers is between +2 and -1. The deviation for P/D = 1.34 is higher and amounts for eq (8a) up to +3.5 and for eq. (11) up to +3.0. The “BREST square”-correlation eq. (13) gives for both P/D ratios over the whole Péclet number range Nusselt numbers below those obtained with eq. (14), albeit it is quoted that eq. (13) is adjusted to the same data. So also the “BREST square” correlation, like the “BREST triangular” correlation (see section 2.2), seems to be a not qualified “conservative” approach. Neither the CFD analysis [20] gives sufficient information to deduce a relation between Nusselt numbers in triangular and square rod arrays covering the interesting Péclet number and P/D-ratio range, nor does the very limited experimental database allow to rely on the resultant correlation, but both do not support the increase of Nusselt numbers in square rod arrays as suggested by eq. (12). So, as long as no more exhaustive CFD analyses or further experimental investigations are available, it is recommended to use for square fuel rod arrays also the correlation recommended for triangular arrays, i.e. the Subbotin/Ushakov correlation eq. (8a) or eq. (8) respectively.

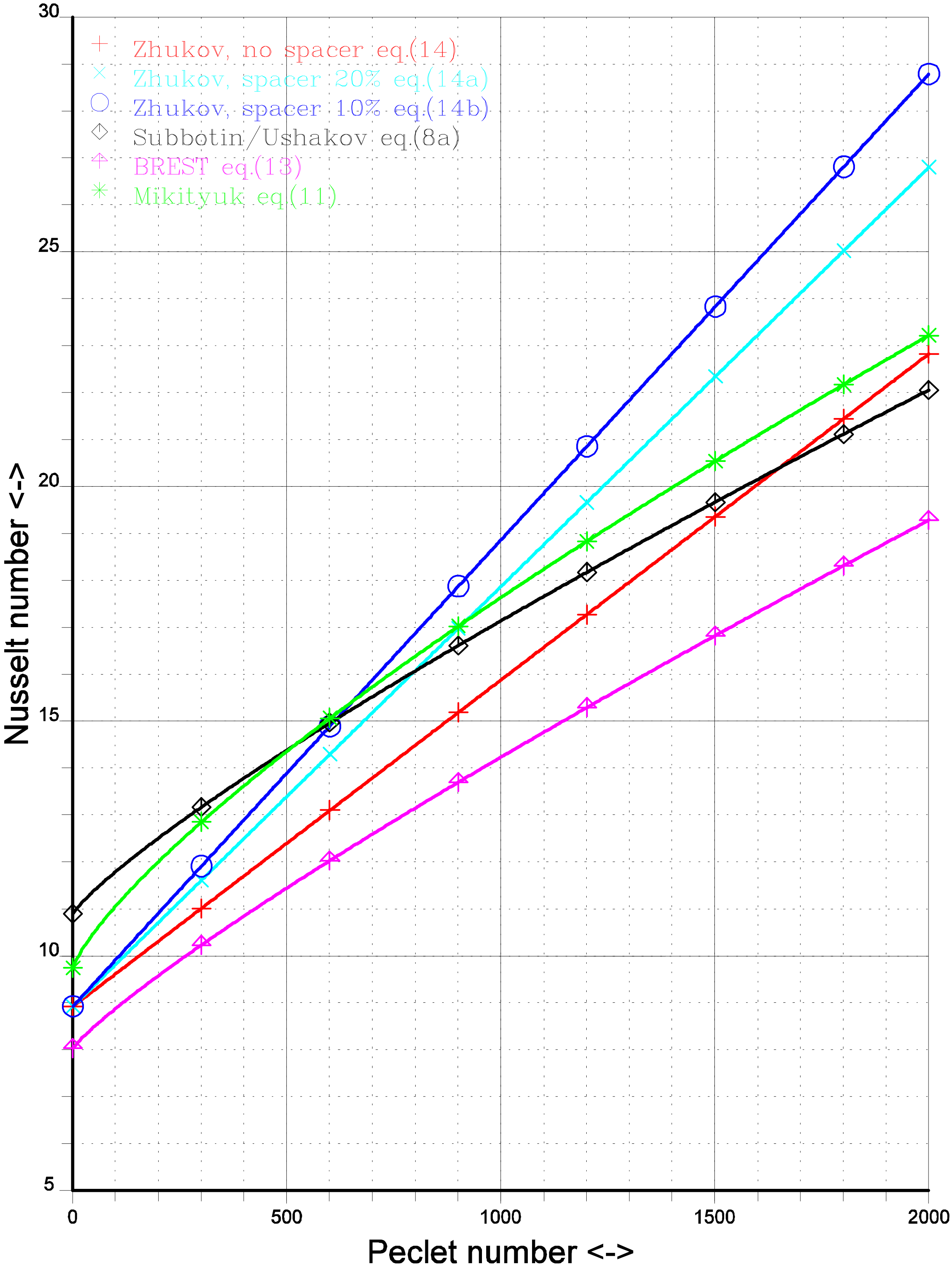

Fig. 4: Correlations for the heat transfer in square arrays at P/D = 1.46

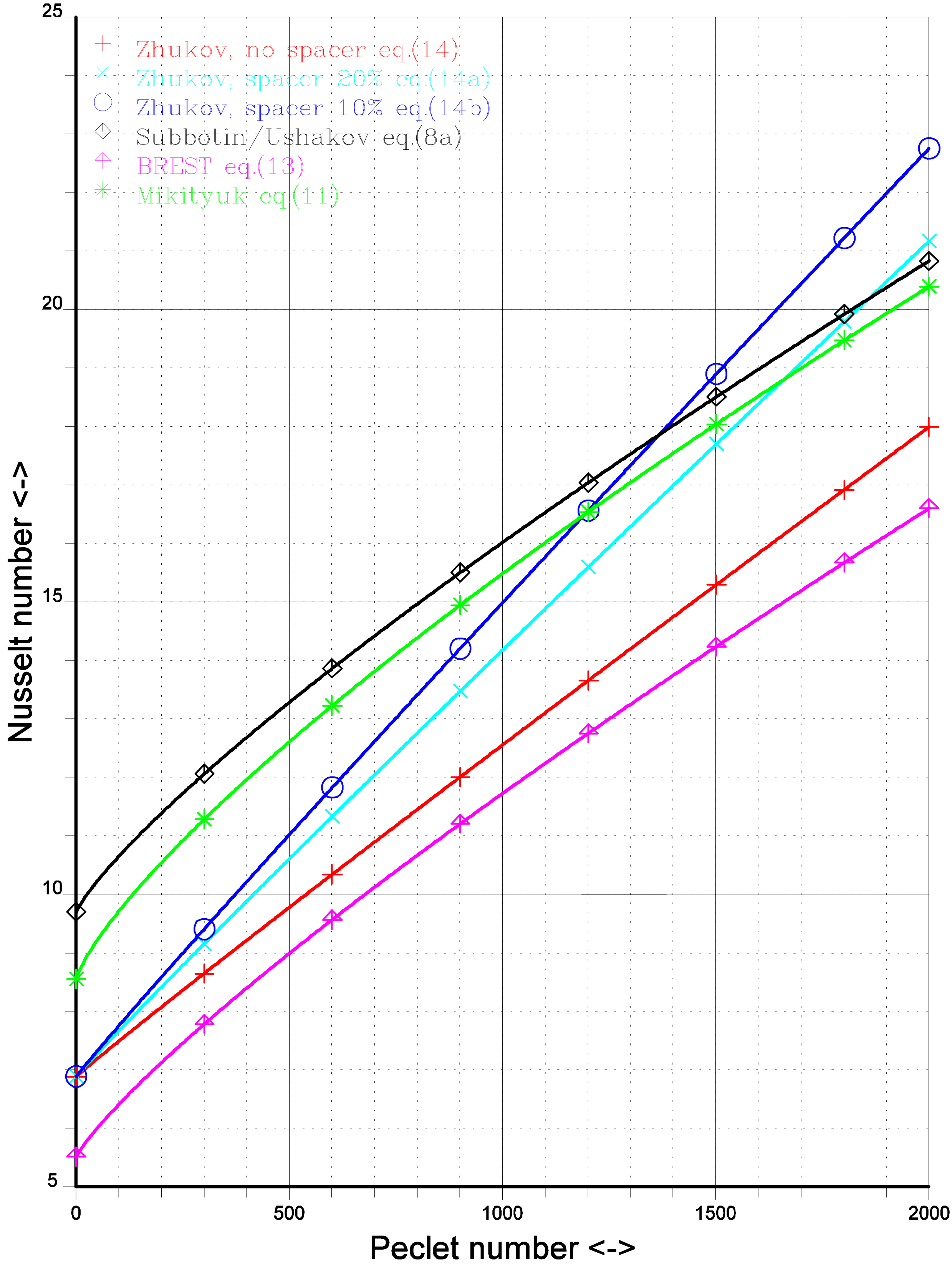

Fig. 5: Correlations for the heat transfer in square arrays at P/D = 1.34

2.4 Influence of spacers

In most of the available publications on experimental campaigns no hint is given, whether spacers or what type of spacers have been used. M. W. Maresca and O. E. Dwyer in [7] and S. Kalish and O. E. Dwyer in [8] state explicitly that "unbaffled bundles of circular pins" are used, i.e. that no spacers are used. In the description of the experimental setup analyzed by H. Gräber and M. Rieger [11] and [24] spacer grids are mentioned and in the sketches of the test section it can be seen that two to three spacer grids are used. A photograph of a spacer grid in [24] shows that it consists of short thin tubes connected with thin plates. Obviously, these spacer grids do not have a significant influence on the heat transfer since the results are within the scatter band of results obtained in setups without spacers.

This is in contrast to the results of A.V. Zhukov et al. [22] (see section 2.3 and Figs. 4 and 5), where the Nusselt number e.g. at Pe = 2000 increases up to about 26 % due to the presence of a spacer. A drawing of the spacer is not given, but it seems to be relatively complicated: "The construction of the spacer grids is a framework made from plates inserted one into another…that form square cells; miniature spring-type protuberances are attached to their walls that contact with the smooth simulators of the fuel rods". Locally, near the spacer, the Nusselt numbers are in the peak value more than doubled. The correlation developed for obstruction of the coolant flow area by the spacer (ε_g) of 10 % gives higher values than that for ε_g = 20 %. It has to be noted that these correlations have been developed by averaging over the stabilized region, for ε_g = 20 % the length of stabilization is longer than for ε_g = 10 %. The authors state that, when averaging over the whole length, it could turn out that the results for ε_g = 20 % would be identical to or even higher than those for ε_g = 10 %.

It seems that the effects of spacers are very much dependent on their design. Experimental investigations of different designs are expensive and time consuming. It could be a valuable task to analyze these with CFD tools.

Dependent on the influence of the actual spacer it should be discussed whether in the computer codes used for the thermal analysis of reactor cores it is necessary to apply axially dependent Nusselt correlations or whether one can stick to averaged correlations.

2.5 Influence of axially dependent heat flux

All correlations presented in this paper have been developed for axially constant heat flux. This boundary condition can be established when using electrically heated fuel rod simulators, but cannot be achieved in a reactor. A. V. Zhukov et al. showed in [21] for cosine axial power profiles that the local Nusselt numbers in the lower core part are increased, in the upper part decreased. Dependent on the steepness of the power profile the deviations in the extremities can reach up to about 40 %. It is not clear whether in this investigation the effect of axially decreasing Péclet numbers due to heat-up is respected.

The effect of axially varying Nusselt numbers should be reviewed in detail, because especially the peak cladding temperatures, which are reached near the top of fissile, could be affected.

3 Concluding remarks

Experimental investigations to study the heat transfer in liquid metals have preferably used mercury (Hg) and sodium–potassium alloy (NaK), sometimes sodium (Na) and, for tube flows, also lead-bismuth alloy (LBE) has been used. The Prandtl numbers of lead and LBE are in the same range as those of Hg and NaK [5]. Some developers of correlations assessed experimental data from campaigns using different coolants and none of the respective publications reported on differences, which could be attributed to that. So the correlations given in this report, which are not explicitly dependent from the Prandtl number, can be used for lead and LBE without restriction.

The database for rod bundles with triangular rod arrangements, which has been used to adjust the correlations, is relatively extended, but it has to be noted, that the respective experiments have all been performed before 1975.

For rod bundles with square arrangement of the rods, the situation is different. There exists only one experimental setup with a very limited number of data points. To improve this situation further experimental investigations are necessary, also CFD analyses evaluating the differences between triangular and square arrangements with regard to Nusselt numbers could help. The simple geometrical transformation from triangular to square arrangement is obviously not valid.

It has been outlined that the correlations have been developed for constant heat flux conditions. In reactor conditions the axial power distribution and in consequence the heat flux is not constant; this leads to an axially dependent correlation for the Nusselt number. This effect has to be evaluated furthermore.

It has been shown that spacers can enhance the heat transfer substantially, especially near the spacer. This has to be kept in mind if spacers are used which alter the coolant flow considerably.

The experimental campaigns addressed in this assessment used cleaned coolants. Remarks that the results could be influenced by layers on the cladding have not been found. Therefore, it can be assumed that the correlations are valid for “clean” coolant conditions. The consequences of possible oxide layers on the cladding should not be packed into the Nusselt number correlations but modelled separately in the computer codes.

4 Abbreviations

BREST	300 MW_{el} and 1200 MW_{el} lead cooled fast reactors, Russia, project started 1998
CFD	Computational fluid dynamics
CFX	CFD code (ANSYS)
CRBR	Clinch River Breeder Reactor, 380 MW_{el} sodium cooled demonstration fast reactor, USA, construction stopped
EFIT	European Facility for Industrial Transmutation (EUROTRANS)
ELSY	European Lead Cooled System, waste transmutation in a lead cooled critical system
EUROTRANS	EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System
FFTF	Fast Flux Test Facility, 400 MW_{th} sodium cooled experimental fast reactor, USA, 1980 - 1992
IPPE	Institute of Physics and Power Engineering, Obninsk, Russia
Hg	Mercury
LBE	Lead-bismuth eutectic alloy
Na	sodium
NaK	Sodium-potassium alloy
Nu	Nusselt number
Pe	Péclet number
Pr	Prandtl number
P/D	Pitch to diameter
Re	Reynolds number
TRAC/AAA	Thermal-hydraulics system code for advanced fast reactors (LANL/USNRC)
XT-ADS	Experimental facility, which has the aim to demonstrate the technical feasibility of transmutation in an accelerator driven system (EUROTRANS)
ε	"Approximate criterion of thermal similarity of fuel rods"
ε_g	Ratio of coolant flow cross section obstruction by a spacer
ε_H	Eddy diffusivity of heat
ε_M	Eddy diffusivity of momentum
Ψ	Ratio of $\varepsilon_{H \text{ and }} \varepsilon_M$

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