

# HEAT TRANSFER TO LIQUID METAL: DATA AND CORRELATIONS FOR TUBE BUNDLES

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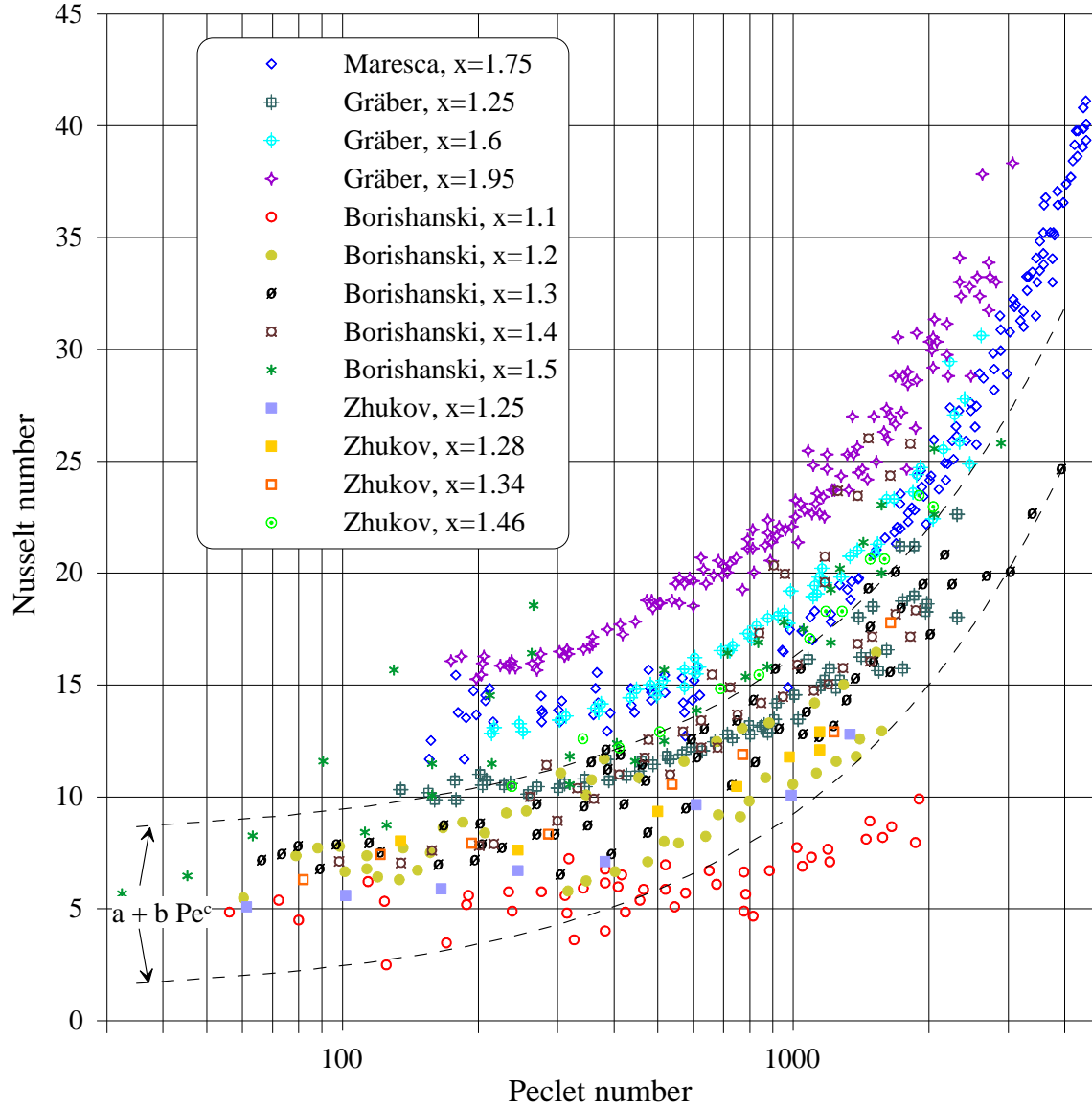
# Outline

- + Liquid metal / tube bundle data review
- + Liquid metal / tube bundle correlation review
- + Analysis of correlation quality for predicting the data
- + Application of the correlations to ELSY conditions
- + Recommendation and conclusion

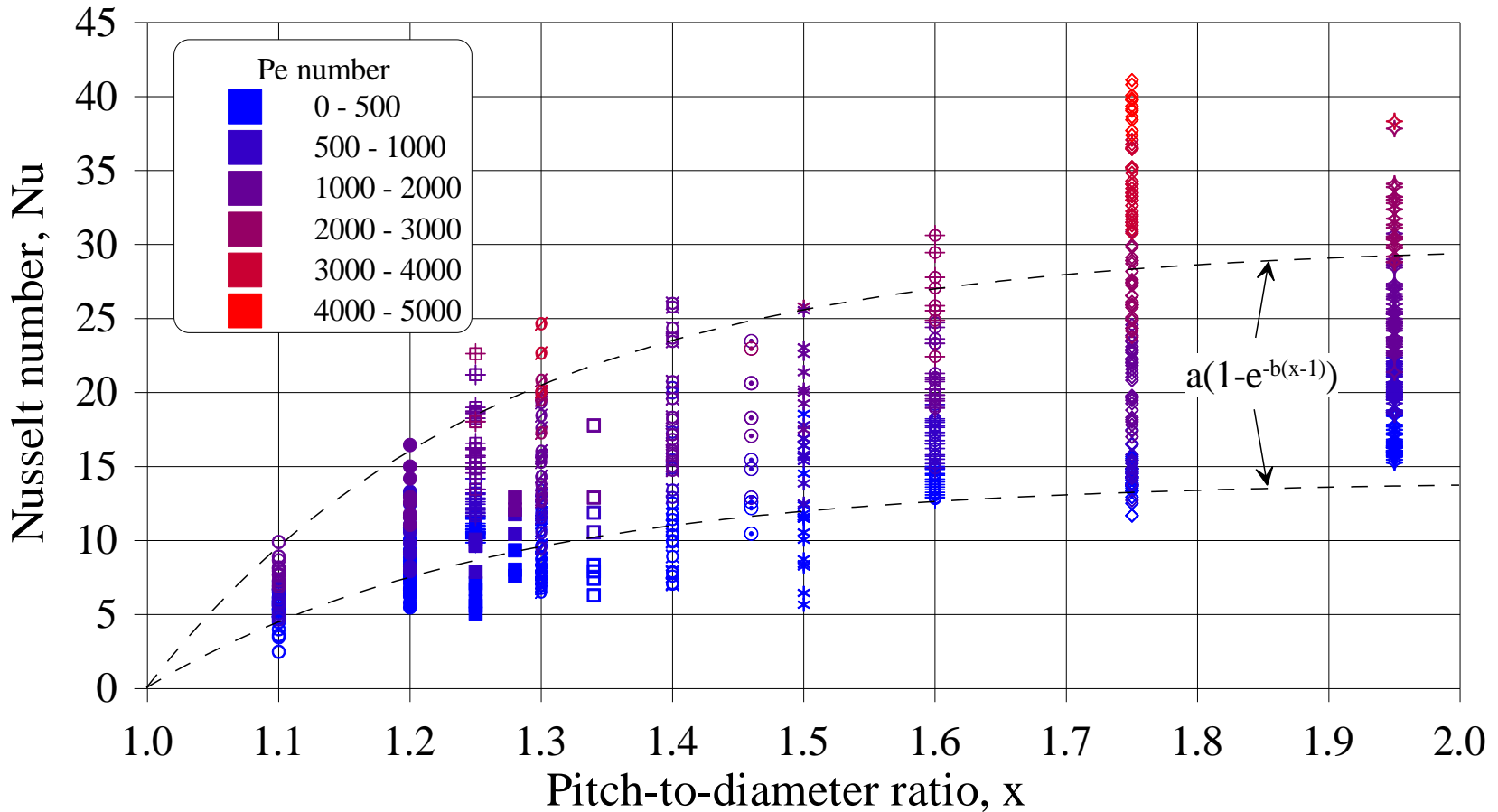
# Test data

Name	Tubes	Ø, mm		x	Fluid	N	Pe
Maresca	13	13	△	1.75	Hg	146	150...4000
Borishanski	7	22	△	1.1, 1.3, 1.4, 1.5	Na-K ?	230	30...2000
Gräber	31	12	△	1.25, 1.6, 1.95	44Na-56K	246	110...4300
Zhukov	25	12	□	1.25, 1.28, 1.34, 1.46	22Na-78K	36	60...2000

# Test data: Nusselt vs Pe



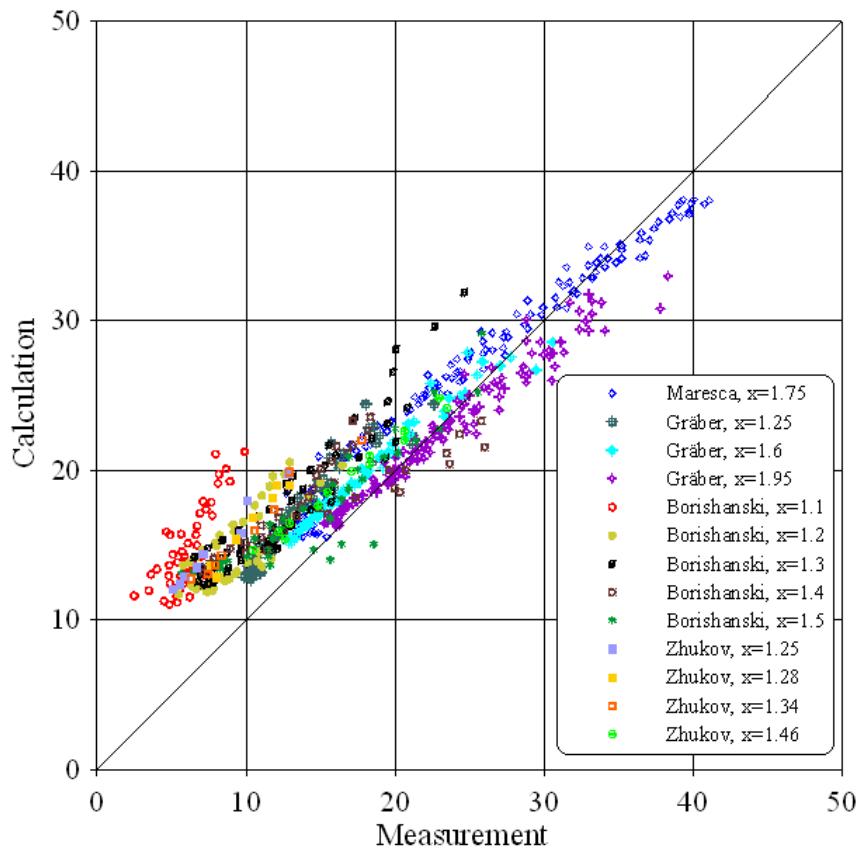
# Test data: Nusselt vs x



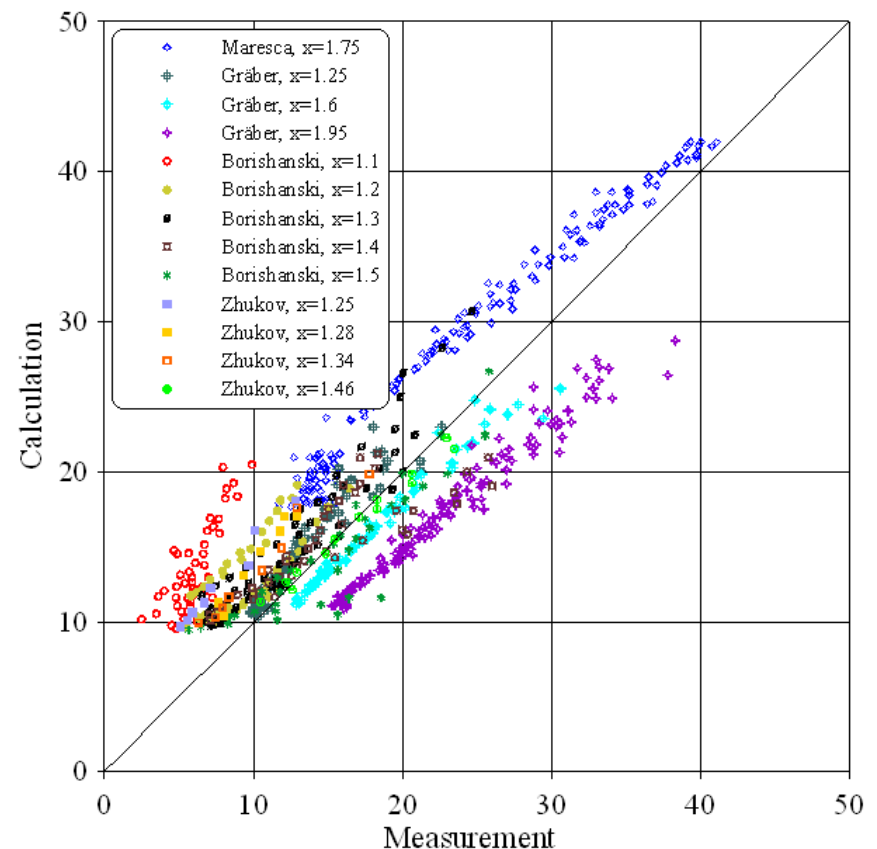
# Correlations

Name	Correlation		Pe	x
Dwyer	$Nu = 0.93 + 10.81x - 2.01x^2 + 0.0252x^{0.273}(\psi Pe)^{0.8}$	△	70...10 <sup>4</sup>	1.375...2.2
Friedland	$Nu = 7.0 + 3.8x^{1.52} + 0.027x^{0.27}(\psi Pe)^{0.8}$	△	0...10 <sup>5</sup>	1.3...10
Maresca	$Nu = 6.66 + 3.126x + 1.184x^2 + 0.0155(\psi Pe)^{0.86}$	△	70...10 <sup>4</sup>	1.3...3.0
Subbotin	$Nu = 0.58\left(\frac{2\sqrt{3}}{\pi}x^2 - 1\right)^{0.55} Pe^{0.45}$	△	400...4000	1.1...1.5
Ushakov	$Nu = 7.55x - \frac{20}{x^{13}} + \frac{0.041}{x^2} Pe^{0.56+0.19x}$	△	0...4000	1.3...2.0
Borishanski	$Nu = 24.15\log(-8.12 + 12.76x - 3.65x^2) + 0.0174(1 - e^{-6(x-1)})B,$ where $B = \begin{cases} 0, & Pe < 200 \\ (Pe - 200)^{0.9}, & Pe \geq 200 \end{cases}$	△	30...2000	1.1...1.5
Gräber	$Nu = 0.25 + 6.2x + (0.032x - 0.007)Pe^{0.8-0.024x}$	△	110...4000	1.25...1.95
Zhukov	$Nu = 7.55x - 14x^{-5} + 0.007Pe^{0.64+0.246x}$	□	10...2500	1.2...1.5
New	$Nu = 0.047(1 - e^{-3.8(x-1)})(Pe^{0.77} + 250)$	△ □	30...5000	1.1...1.95

# Nu measured versus Nu calculated

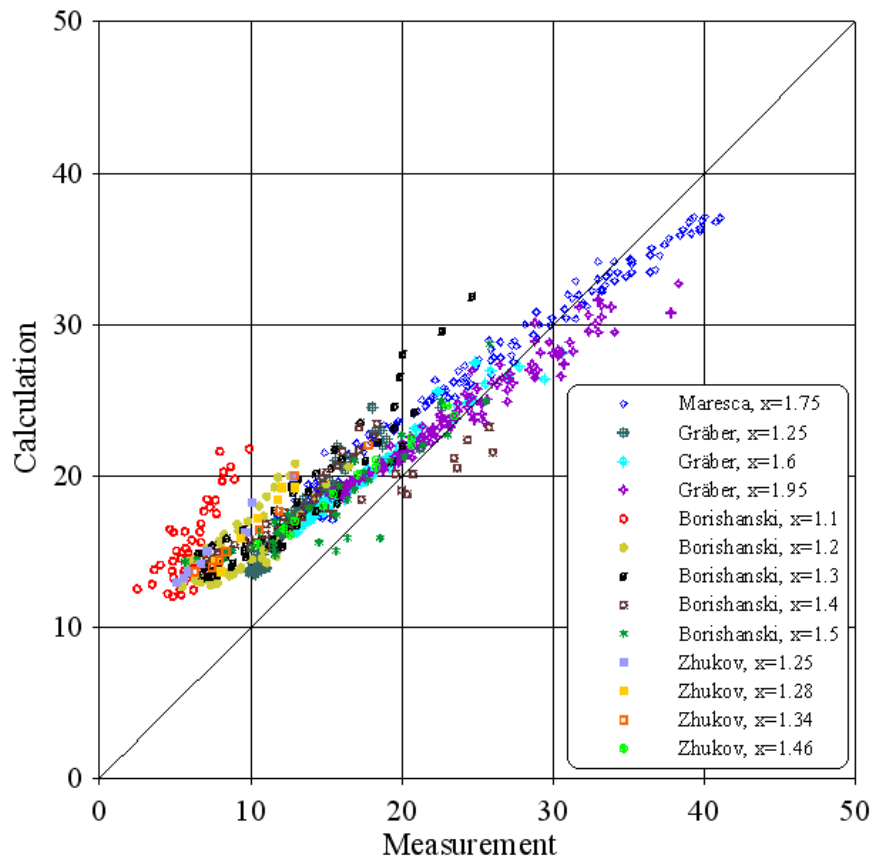


a) Dwyer correlation<sup>1)</sup>

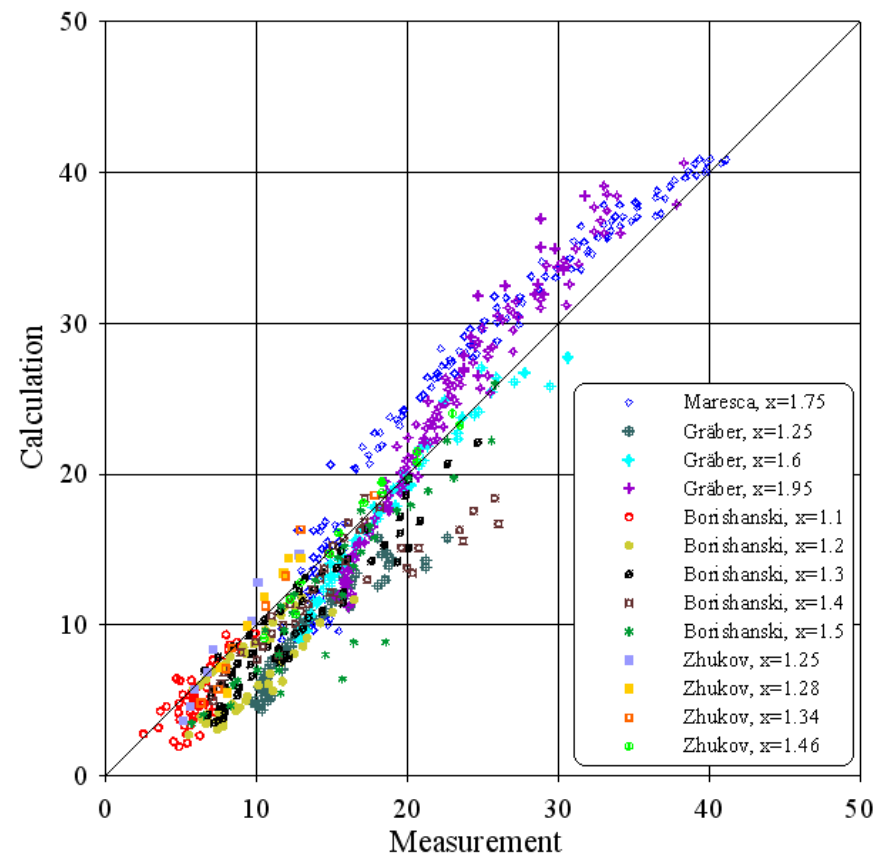


b) Friedland correlation<sup>2)</sup>

# Nu measured versus Nu calculated

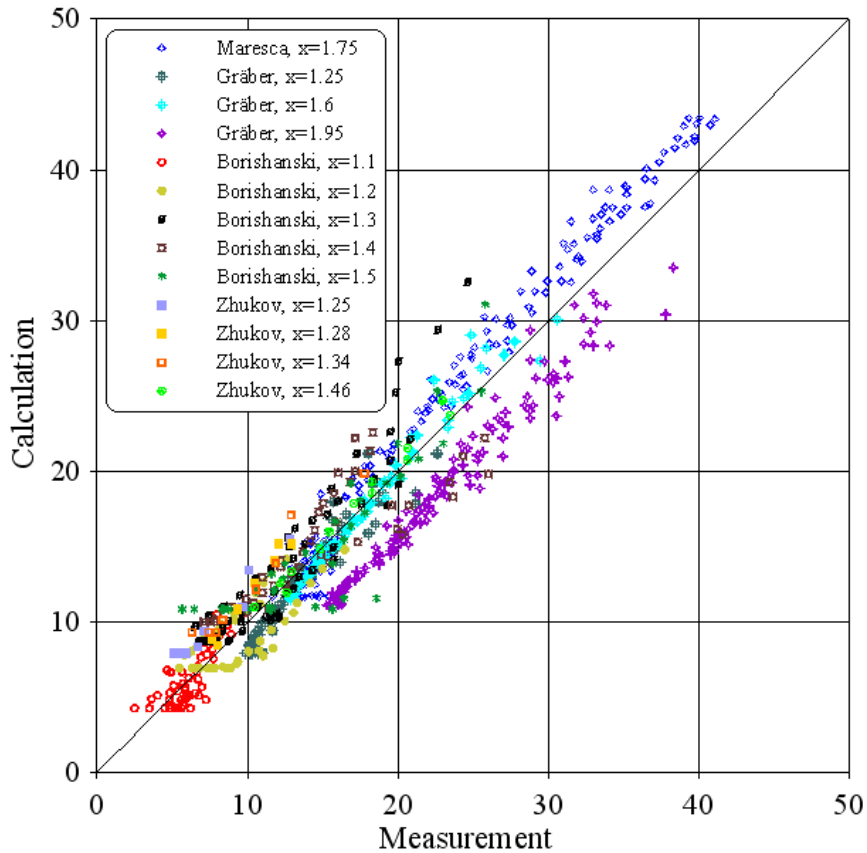


c) Maresca correlation<sup>3)</sup>

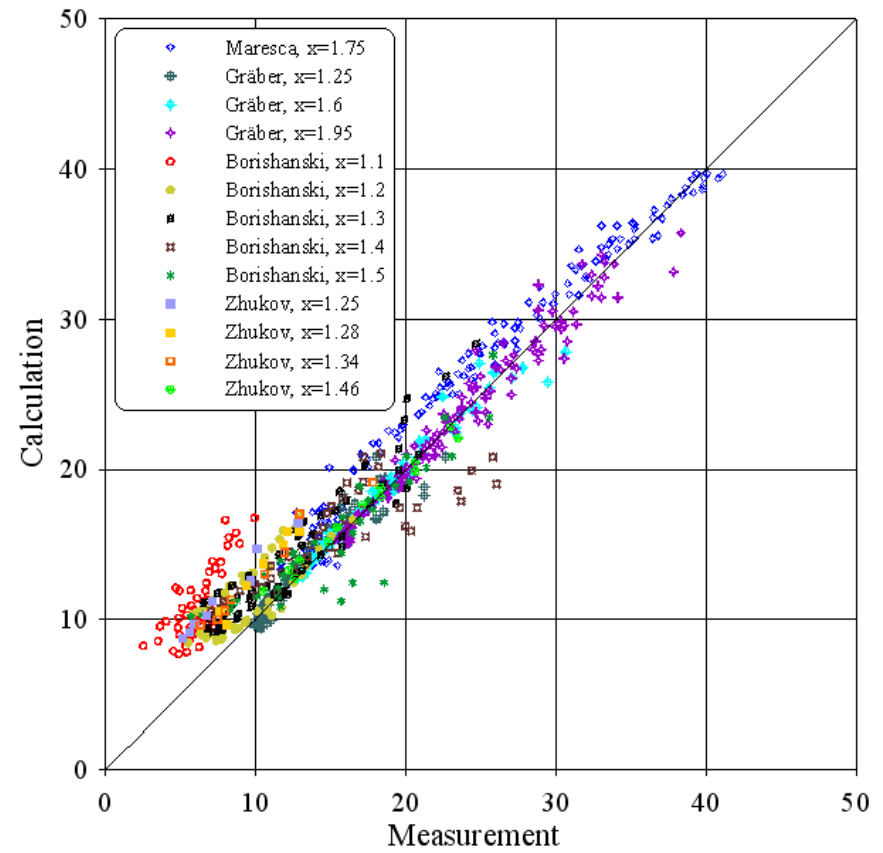


d) Subbotin correlation<sup>4)</sup>

# Nu measured versus Nu calculated

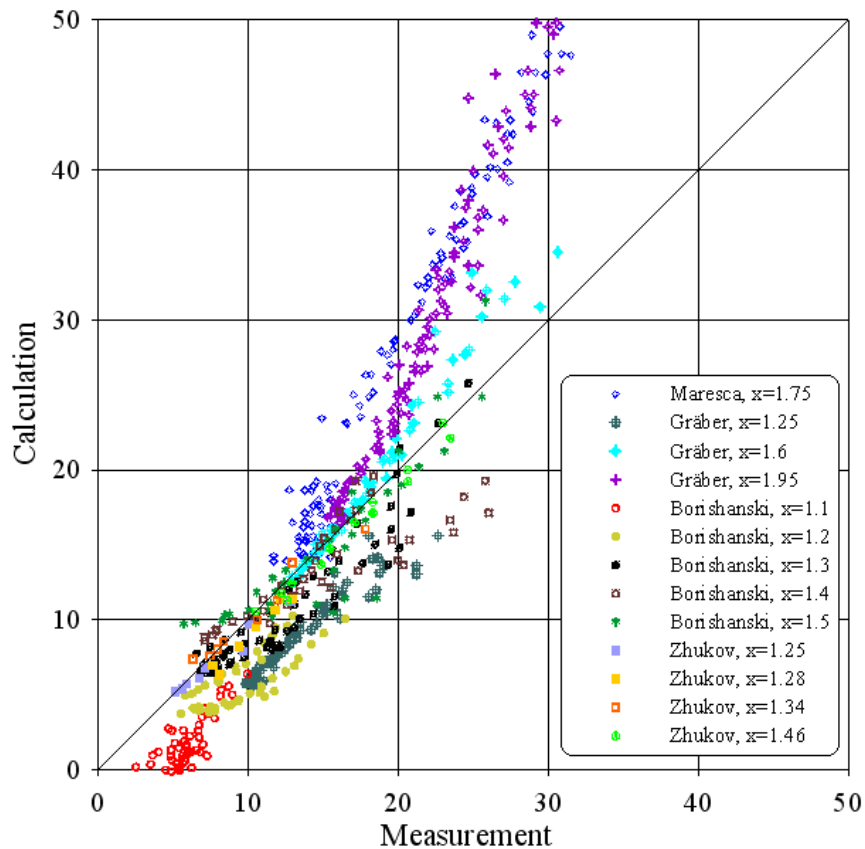


e) Borishanski correlation<sup>5)</sup>

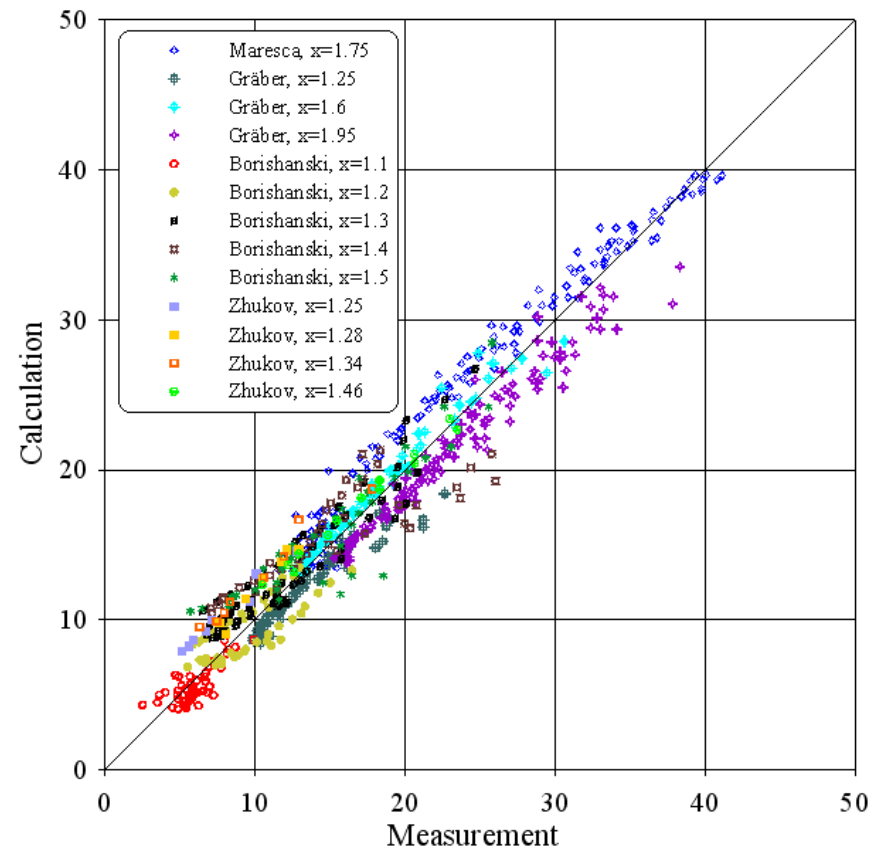


f) Gräber correlation<sup>6)</sup>

# Nu measured versus Nu calculated

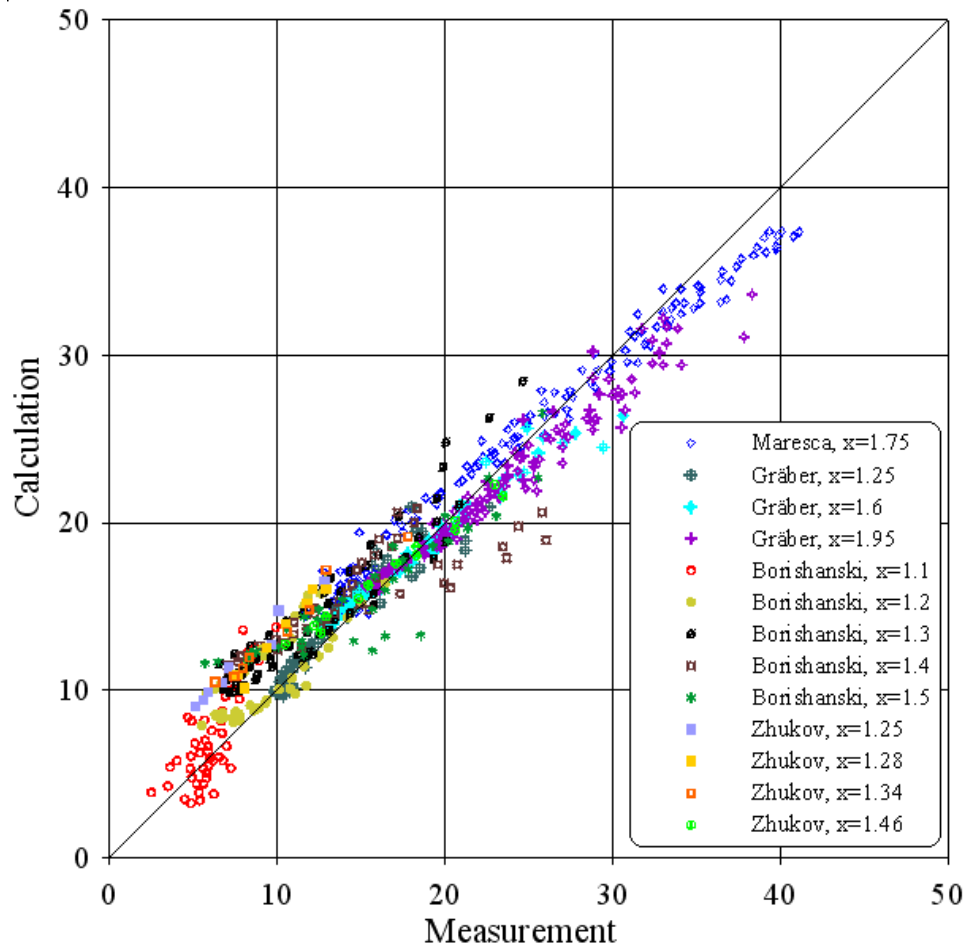


g) Zhukov correlation<sup>7)</sup>



h) This study

# Nu measured versus Nu calculated



a) Ushakov correlation<sup>5)</sup>

# Analysis of quality of correlations

Absolute error for each data point  $\varepsilon_i = \text{Nu}_i^m - \text{Nu}_i^c$

Mean absolute error

$$\bar{\varepsilon} = \sum_{i=1}^N \varepsilon_i / N$$

Standard deviation

$$\sigma = \sqrt{\sum_{i=1}^N (\varepsilon_i - \bar{\varepsilon})^2 / (N - 1)}$$

Root-mean-square error

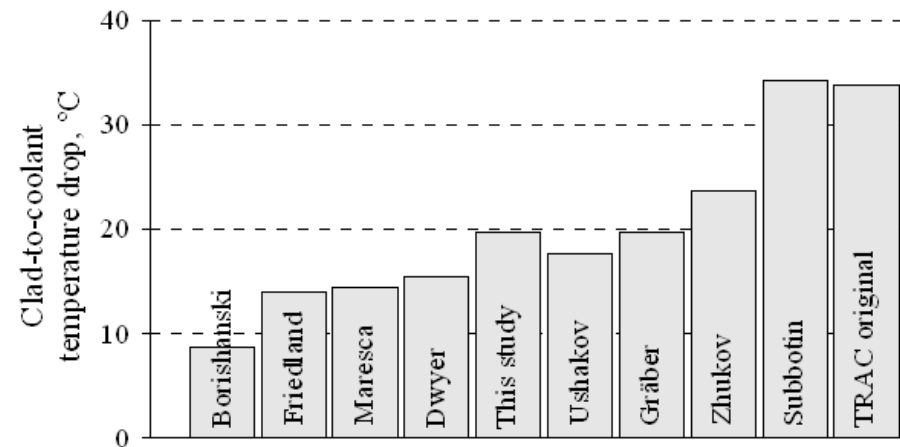
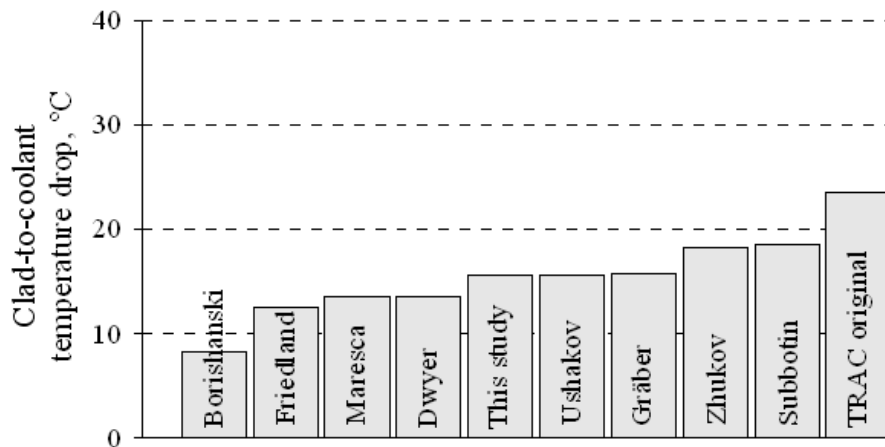
$$r = \sqrt{\sum_{i=1}^N \varepsilon_i^2 / N}$$

# Analysis of quality of correlations

# of data points		Correlations								
		Dwyer	Friedland	Maresca	Subbotin	Ushakov	Borishanski	Gräber	Zhukov	This study
658	$\bar{\epsilon}$	-2.8	-5.1	-3.3	0.5	-0.7	0.4	-1.2	-3.6	-0.1
	$\sigma$	3.1	2.4	3.2	3.0	2.1	2.6	2.0	8.8	1.9
	r	4.1	5.6	4.6	3.1	2.2	2.7	2.3	9.5	1.9

# TRAC analysis of correlations in ELSY conditions

	Normal	LOF
Coolant velocity, m/s	1.0	0.2
Coolant temperature, °C	483	818
Peclet number	992	162



# Conclusions

- + Only tube bundle data considered
- + No “dirty” fluid data considered:
- + Influence of oxide layer → direct simulation
- + Not enough data to see  $\triangle$  /  $\square$  difference
- + Ushakov correlation recommended
- + Published in Nuclear Engineering and Design, 239, pp. 680-687 (2009)