KIT activities for Verification & Validation of Liquid Metals Thermal Hydraulics
- CFX + variable turbulent Pr number
- TRACE + empirical models

Institute for Neutron Physics and Reactor Technology

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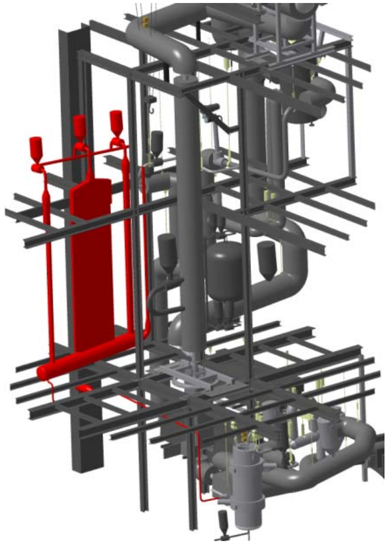
Institute for Neutron Physics and Reactor Technology



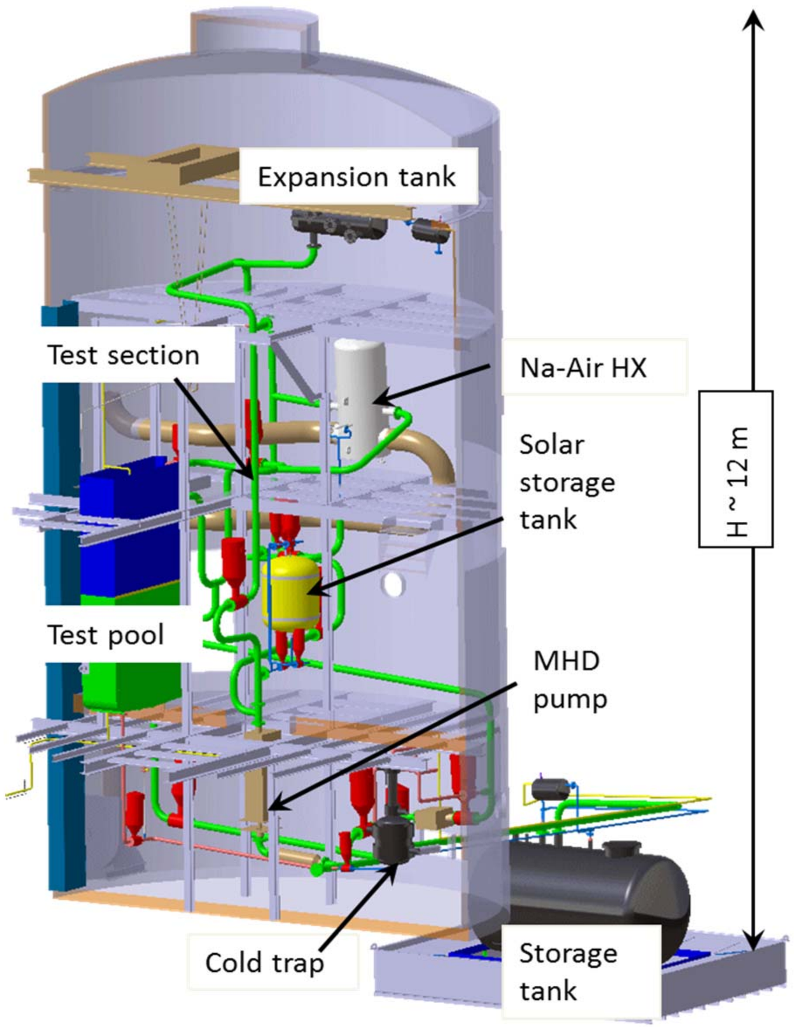
Motivation

At the INR a large sodium loop (7 m³; 37 m total length, up to 150 m³/h) is under construction along with smaller liquid metal cooled loops.

Furthermore, other liquid metal cooled facilities exist at the KIT (e.g. KALLA).

In addition, the INR is involved in several European projects for liquid metal cooled facilities/reactors (e.g. MYRRHA).

Therefore, validated tools are needed for the design, operation and demonstration of safety of these loops/plants.



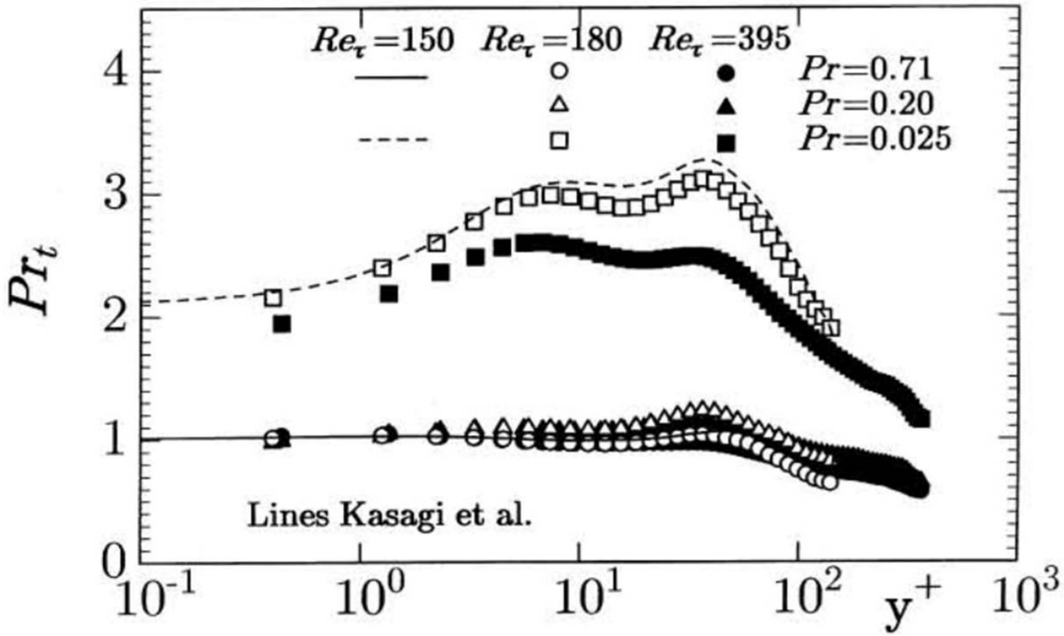
KArlsruhe SOdium LAboratory - KASOLA

Turbulent Prandtl Number Concept

$$Pr_{turb} = \frac{\nu_{turb}}{\lambda_{turb}} \rho\, cp \quad = f(y+, Re, Pr, \ldots) \quad (1)$$

Very difficult to obtain from measurements especially for liquid metal flows !

DNS of 2D channel flow



Data extension until Re=82000 by Duponcheel et. al.

Idea:

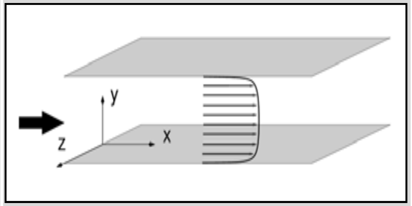
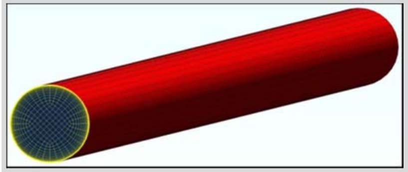
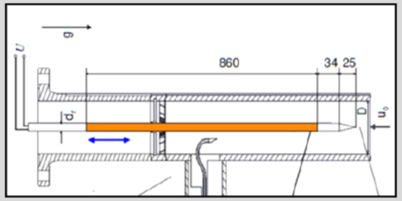
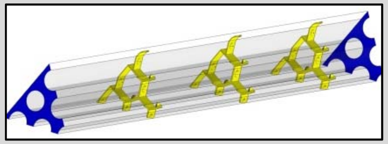
Pr_t from DNS/LES data as 3D look-up tables by Tri-linear Interpolation and use them for similar flow types !

⬇

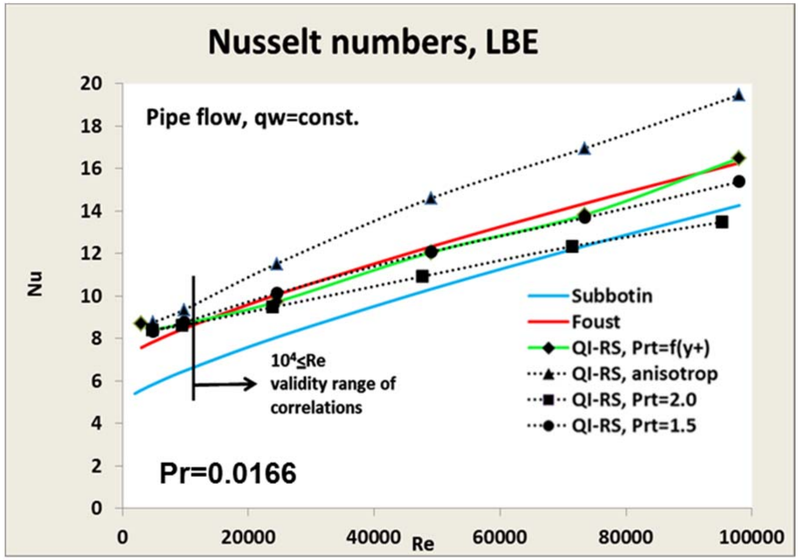
υ_{turb} by RANS turbulence models

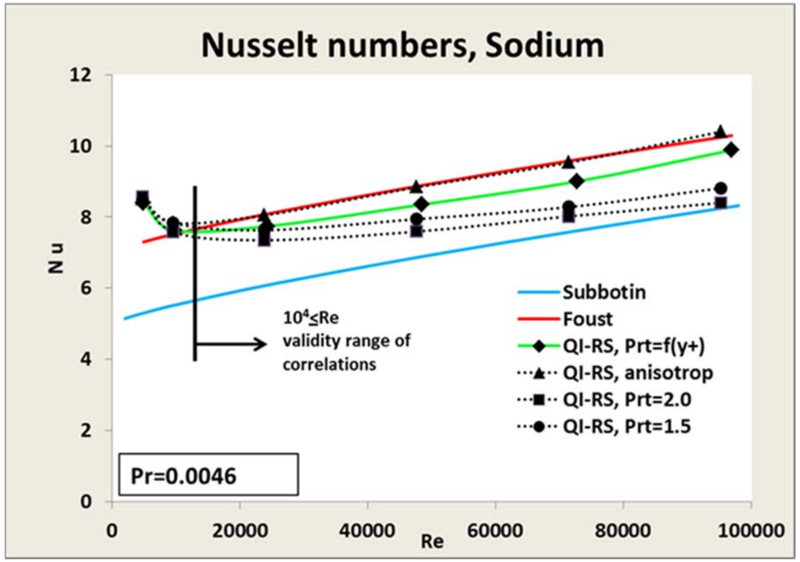
λ_{turb} by (1) and look-up tables

Validation Cases

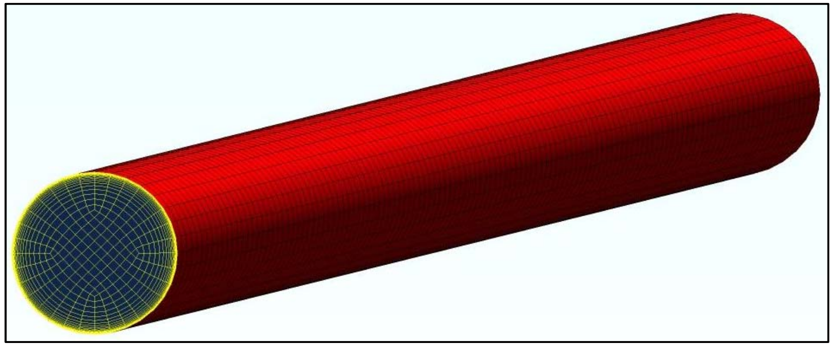
2D channel flow		**Re = 5600, 22000 Pr = 0.01, 0.1, 1 DNS/LES data No buoyancy**
Pipe flow		**Re = 5700 … 111000 Pr = 0.016 …0.0046 Standard correlations Buoyancy included**
Gap flow single pin		**Re = 33000 … 400000 Pr ~ 0.016 (LBE flow) Detailed measurements**
Rod bundle flow Pin assembly		**Re = 7800 … 78000 Pr ~ 0.016 (LBE flow) OECD correlation and measurements**

Validation Cases: Pipe Flow

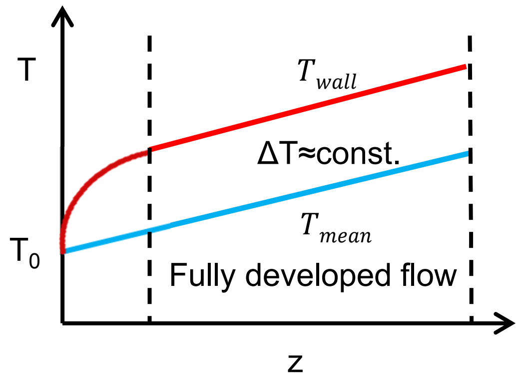




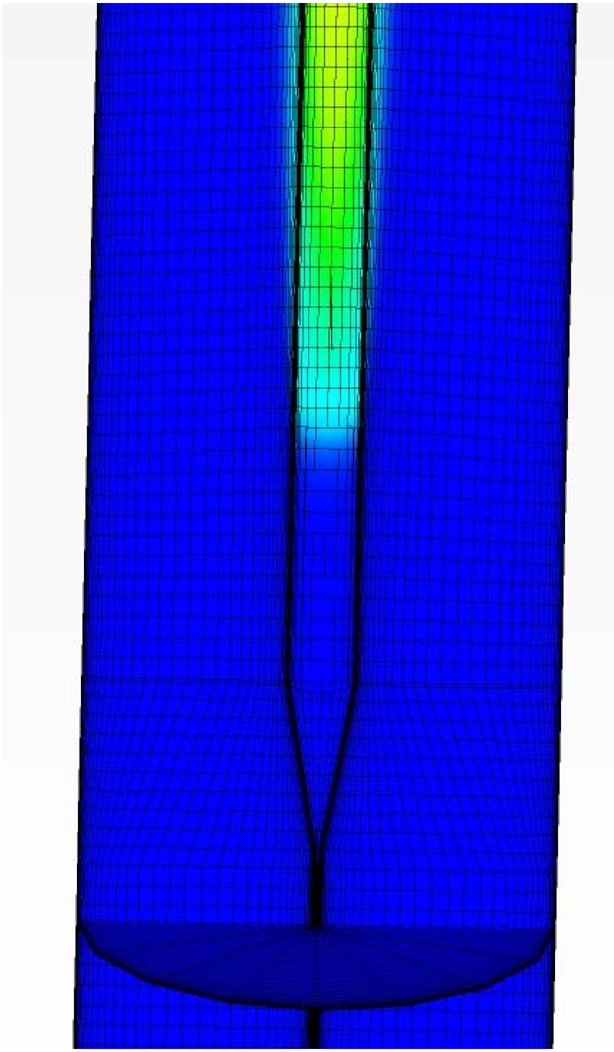
Validation case:
Pipeflow with constant heat flux



CFX-model: 89000 cells
Y^+ = 0.3 …7
D = 9.5mm L = 1.25m



Validation Cases: Single Pin



Model informations:

569 000 elements (16 cells in circumferential direction), structured

SST turbulence model

Buoyancy model with production and dissipation of turbulence

Conjugate heat transfer (pin)

Boundary conditions:

Inlet

Velocity profile (equilibrium)

Constant inlet temperature T_0

Constant turbulence quantities (1%)

Outlet

$\Delta p=0$ [Pa] at the outlet

Pin surface

Heat flux; pin head: heat flux derived from measurements

Other surfaces

adiabatic

Validation Cases: Single Pin

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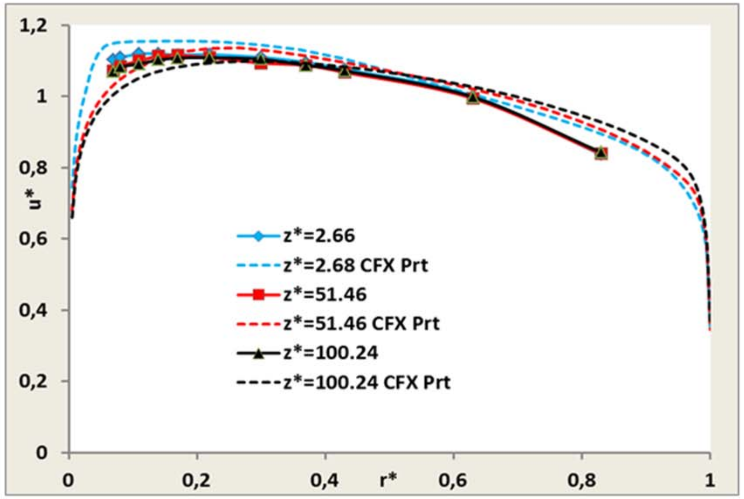
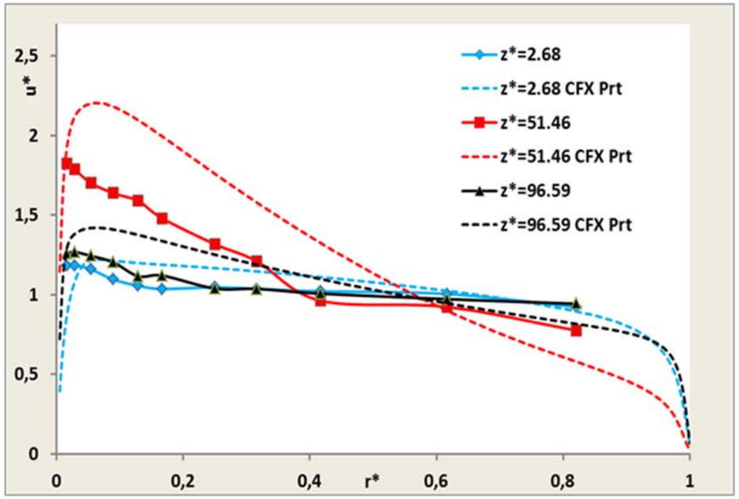
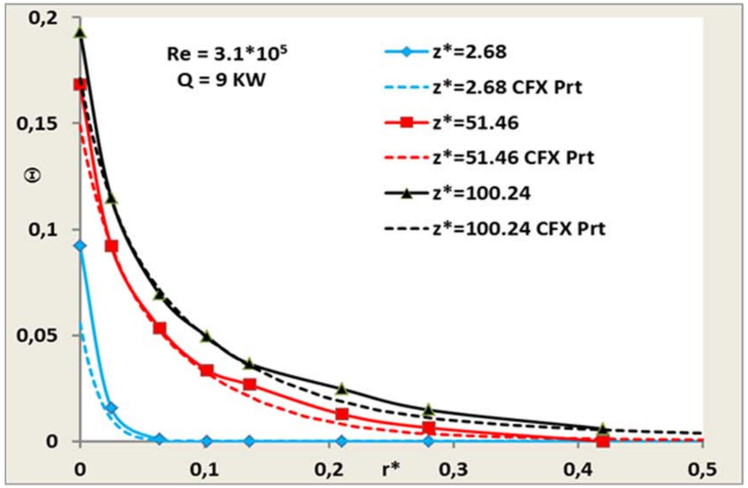
Re=3.1*10⁵, forced convection

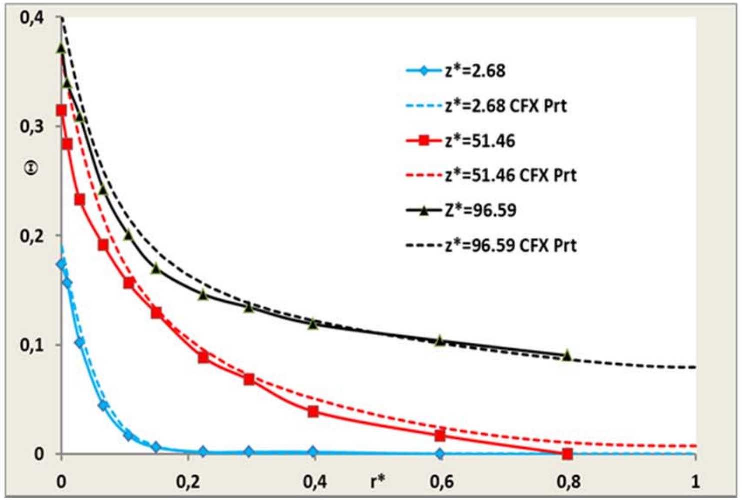
Re=1.9*10⁴, buoyancy dom.





Q=9KW





Validation Cases: Rod Bundle

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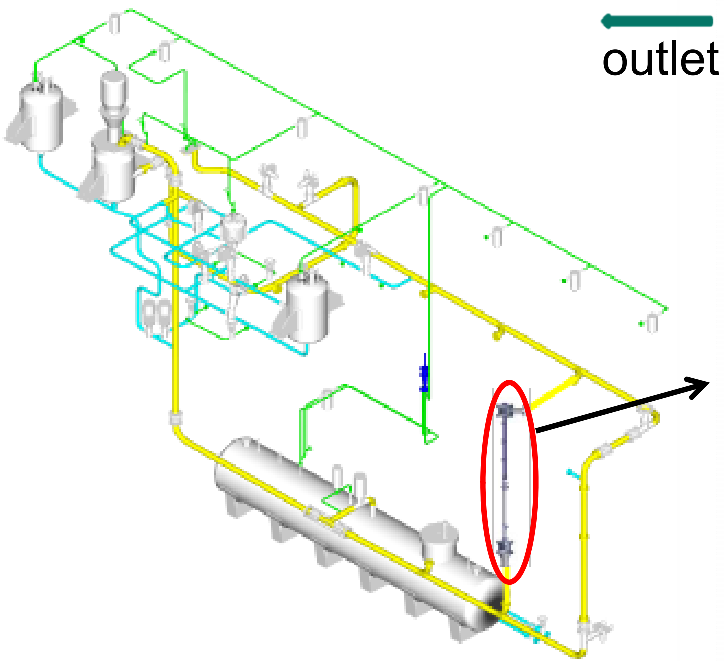
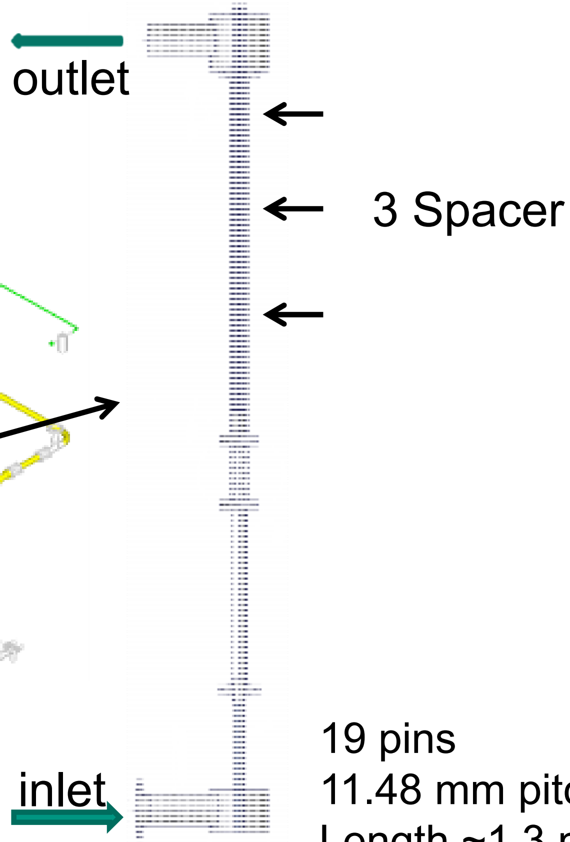
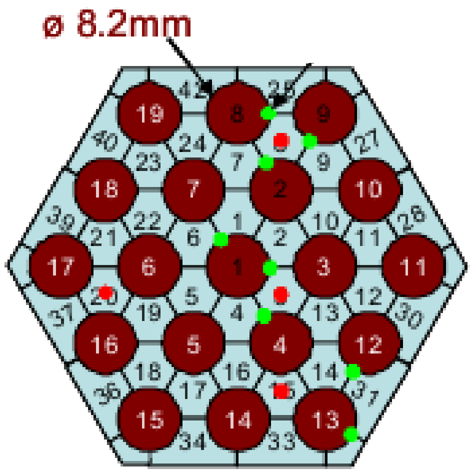
KALLA – **Kar**lsruher **l**iquid metal **la**boratory
THEADES - **The**rmalhydraulics and **ADS** **Des**ign





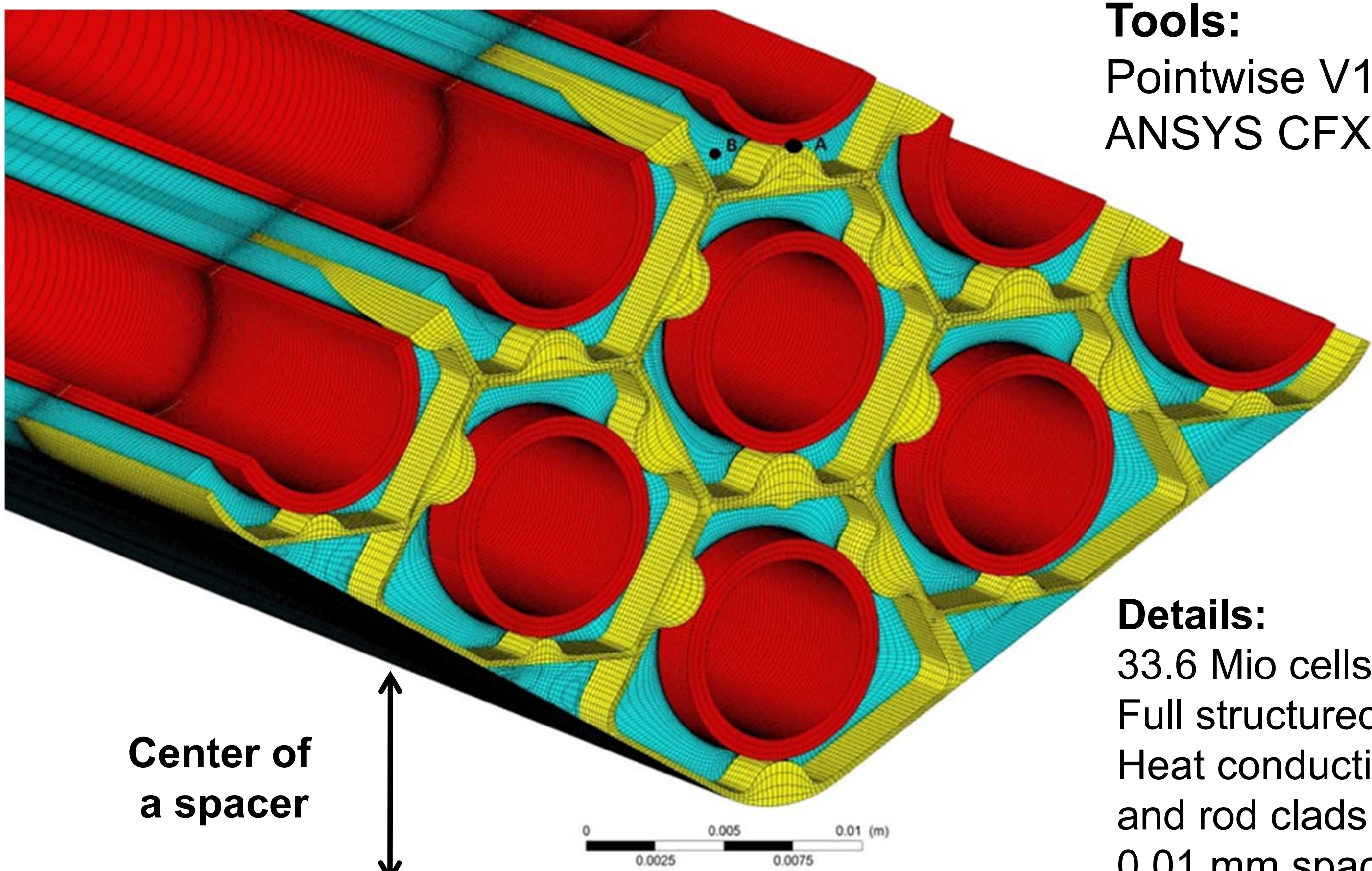


Temperature	190°C-450°C
Flow rate	47 m^3/h
Pressure	5.9 bar
Heating	0.43 MW

Source:
T.Wetzel et. al, IKET

19 pins
11.48 mm pitch
Length ~1.3 m
3 Spacers

Validation Cases: Rod Bundle



Center of a spacer

Tools:
Pointwise V17.1 R4
ANSYS CFX 14.0

Details:
33.6 Mio cells
Full structured, 120° part
Heat conduction in spacers and rod clads
0.01 mm spacing at heated surf.
QI-RS turbulence model
24 CPU-h for steady state

Validation Cases: Rod Bundle

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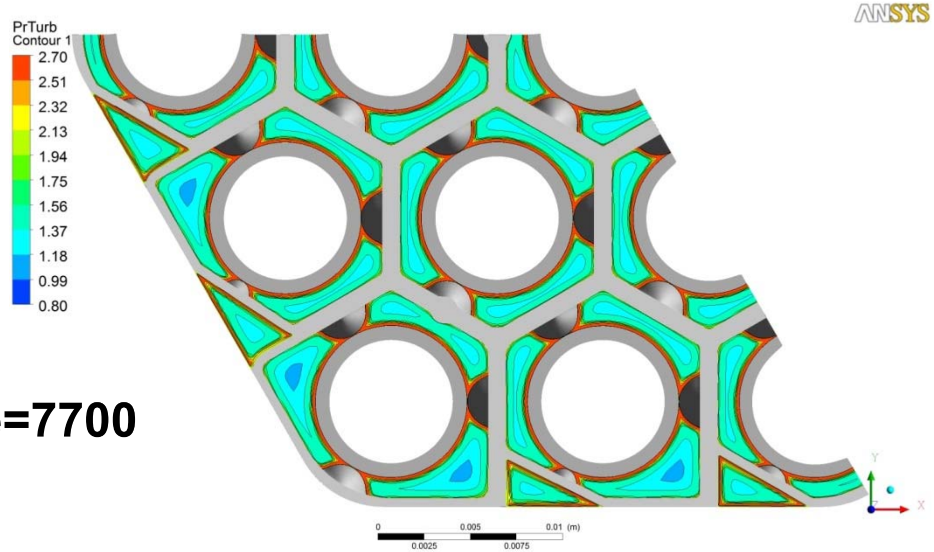
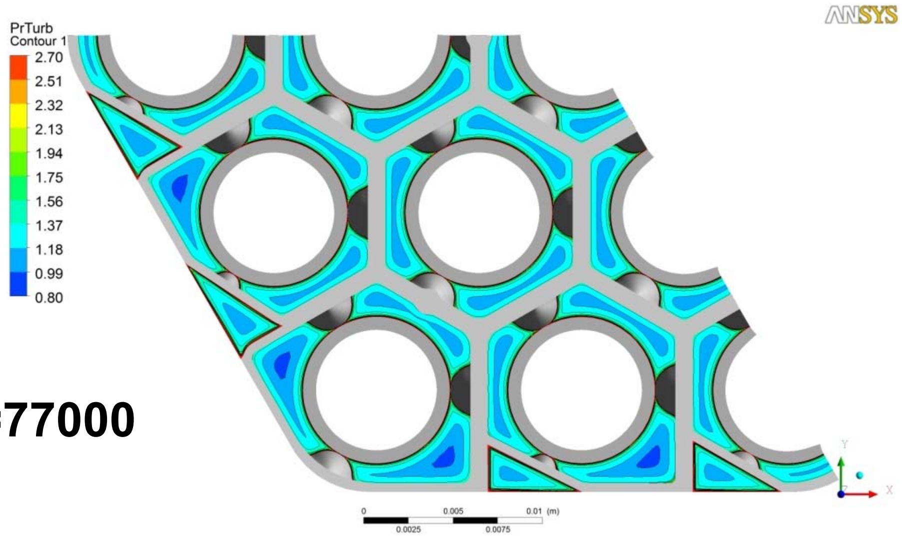


Re=7700

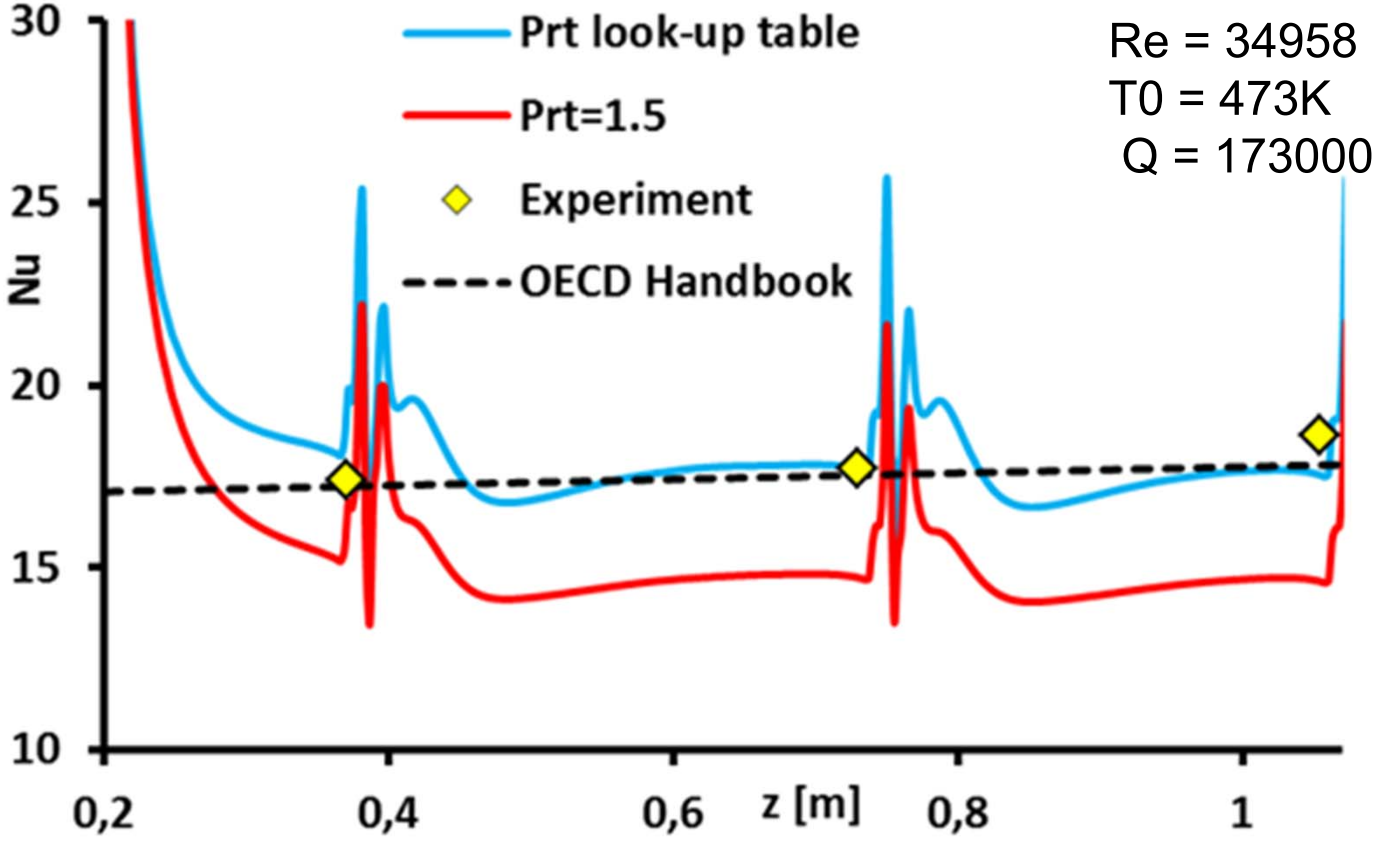
Lower Re:
Significantly thicker thermal layers
Pr_t>1 for most central subchannel regions



Re=77000

Higher Re:
Thinner thermal layers
Higher y^+
Pr_t <1 at central subchannels

Validation Cases: Rod Bundle



Re = 34958
T0 = 473K
Q = 173000 W/m²

OECD Handbook: $$Nu = 7.55\frac{P}{D} - 20\left(\frac{P}{D}\right)^{-13} + \frac{3.67}{90\left(\frac{P}{D}\right)^{2}} Pe^{0.19\left(\frac{P}{D}\right)+0.56}$$

TRACE Closure Models

The standard TRACE code (water with liquid and vapor phase) requires 10 parameters in order to close the field equations.
For single phase liquid metal flow only two parameters are needed.

Parameter	Field equations: Mass Liquid	Mass Gas	Energy Liquid	Energy Gas	Momentum Liquid	Momentum Gas
~~A_i~~	~~X~~	~~X~~		~~X~~	~~X~~	~~X~~
~~Γ~~	~~X~~	~~X~~		~~X~~	~~X~~	~~X~~
~~c_i~~					~~X~~	~~X~~
c_{wl}					X	
~~c_{wg}~~						~~X~~
~~h_{il}~~	~~X~~	~~X~~		~~X~~	~~X~~	~~X~~
~~h_{ig}~~	~~X~~	~~X~~		~~X~~	~~X~~	~~X~~
~~h_{gl}~~				~~X~~		
h_{wl}	X	X	X	X	X	X
~~h_{wg}~~			~~X~~	~~X~~		

c_{wl} → Wall-to-liquid drag coefficient

h_{wl} → Wall-to-fluid heat transfer coefficient

TRACE Closure Models

TRACE LM V&V

Wall Drag

$$\Delta p = \frac{\rho}{2} \cdot v^2 \cdot \left(K + f \cdot \frac{l}{d}\right)$$

Form Loss Coefficient

Friction Factor

Models for low Prandtl number fluids are identical to the ones of mediums with Pr ≈ 1

➔ Implementation of new models is not necessary!

Heat Transfer

$$h = \frac{k}{d} \cdot Nu$$

Models for low Prandtl number fluids differ considerably from fluids with Pr ≈ 1

➔ Implementation of new models is necessary!

Liquid Metals

Original Version

- Sodium (**Na**)
- Lead-Bismuth-Eutectics (**PbBi**)

1st Modification

- Lead (**Pb**)
- Lead-Bismuth-Eutectics (**PbBi**)

Jaeger, W. & Sánchez Espinoza, V.H., "Improvements and Validation of the System Code TRACE for Lead and Lead-Alloy Cooled Fast Reactors Safety-Related Investigations.", *NUREG/IA-0421*. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC, 2013.

2nd Modification

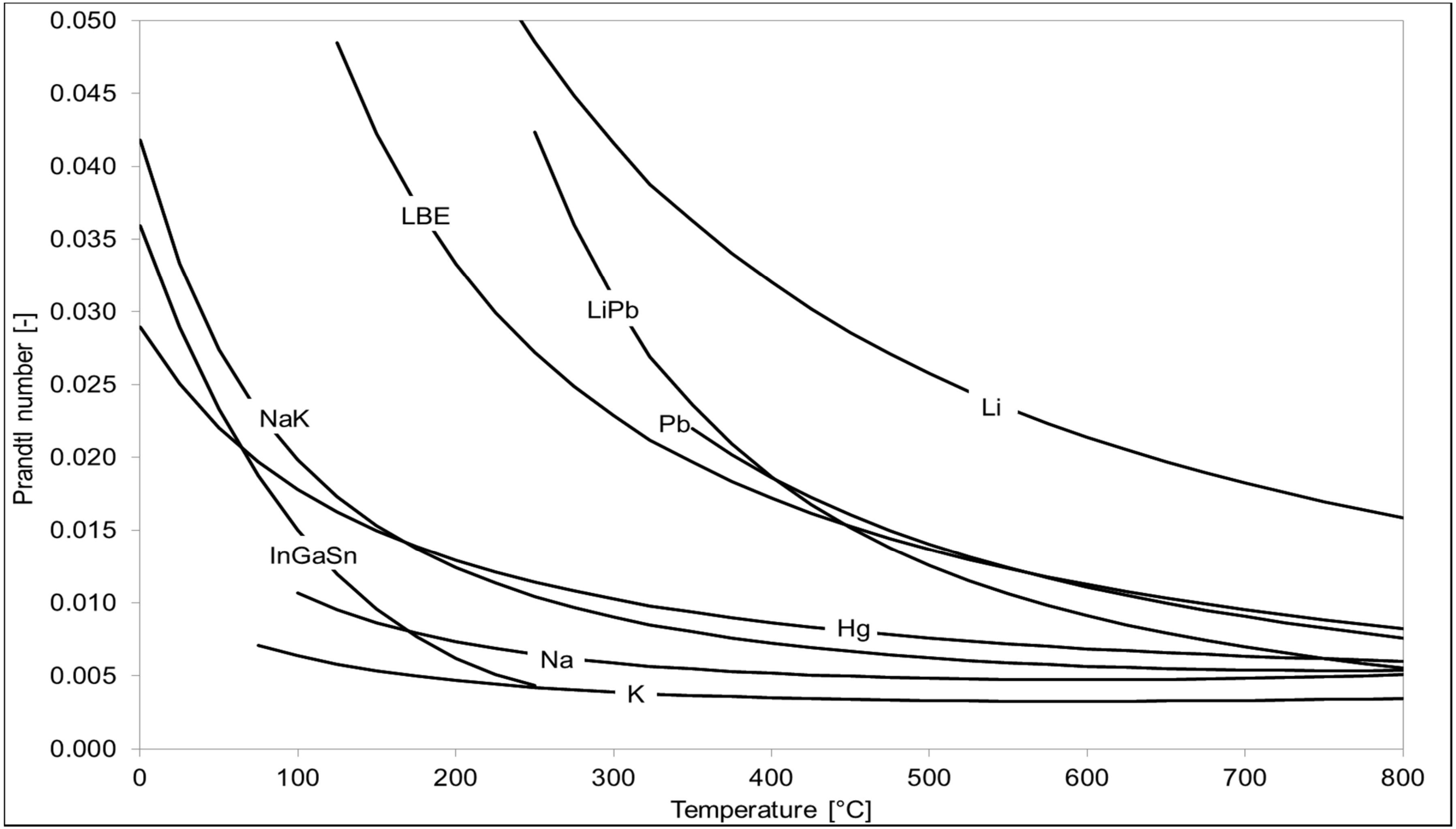
- Potassium (**K**)
- Sodium-Potassium Alloy (**NaK**)
- Mercury (**Hg**)

Jaeger, W., Hering, W., Diez de los Rios, N. & Gonzalez, A., "Validation of TRACE in the field of liquid metal heat transfer.", Proceedings of: *ASME 2014 International Mechanical Engineering Congress and Exposition (IMECE2014)*. Montreal, Canada, 2014.

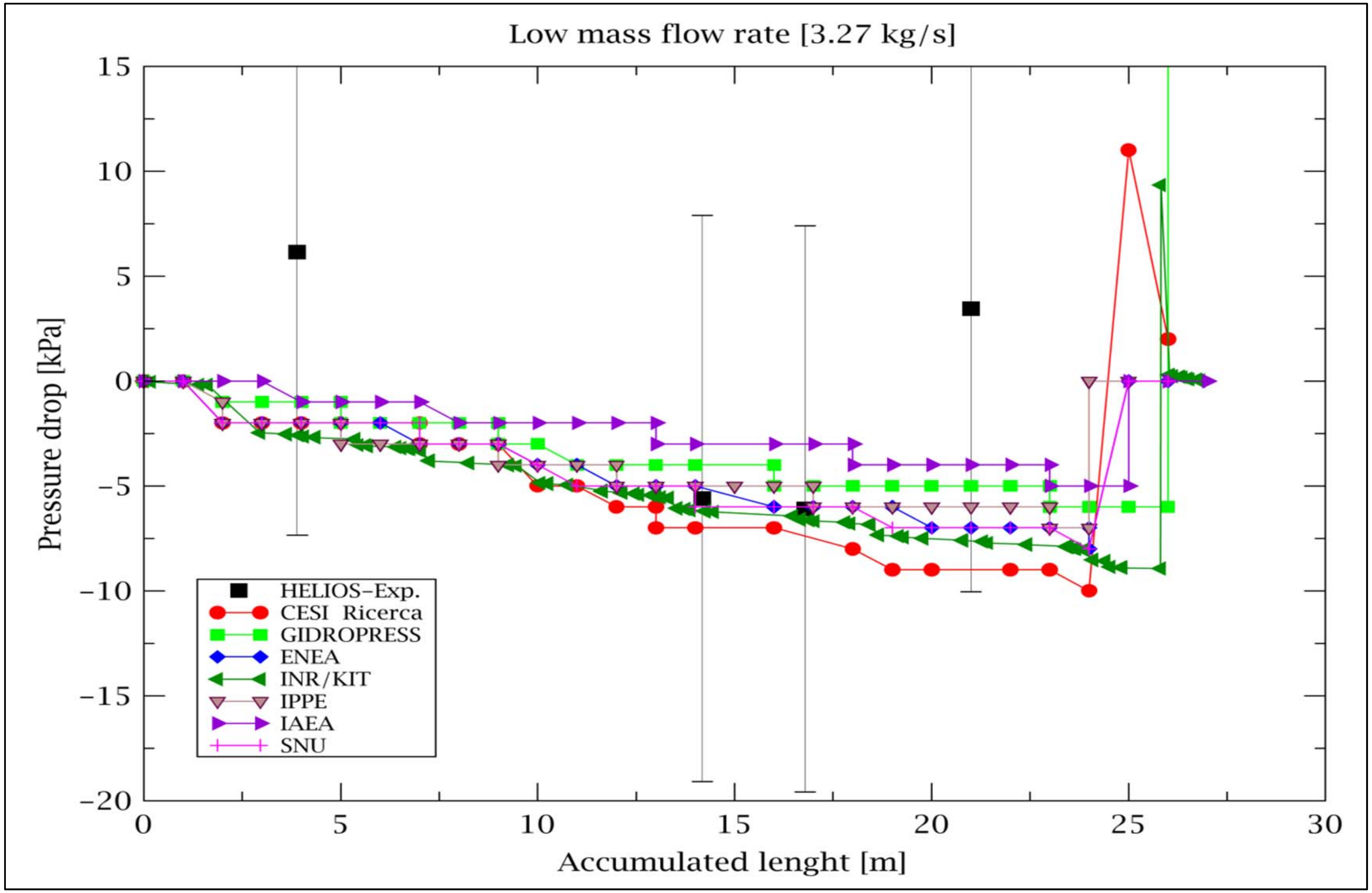
3rd Modification

- Lithium (**Li**)
- Lithium-Lead Alloy (**LiPb**)
- Indium-Gallium-Tin Alloy (**InGaSn**)

Liquid Metals



Wall Drag: LACANES Benchmark 1/2



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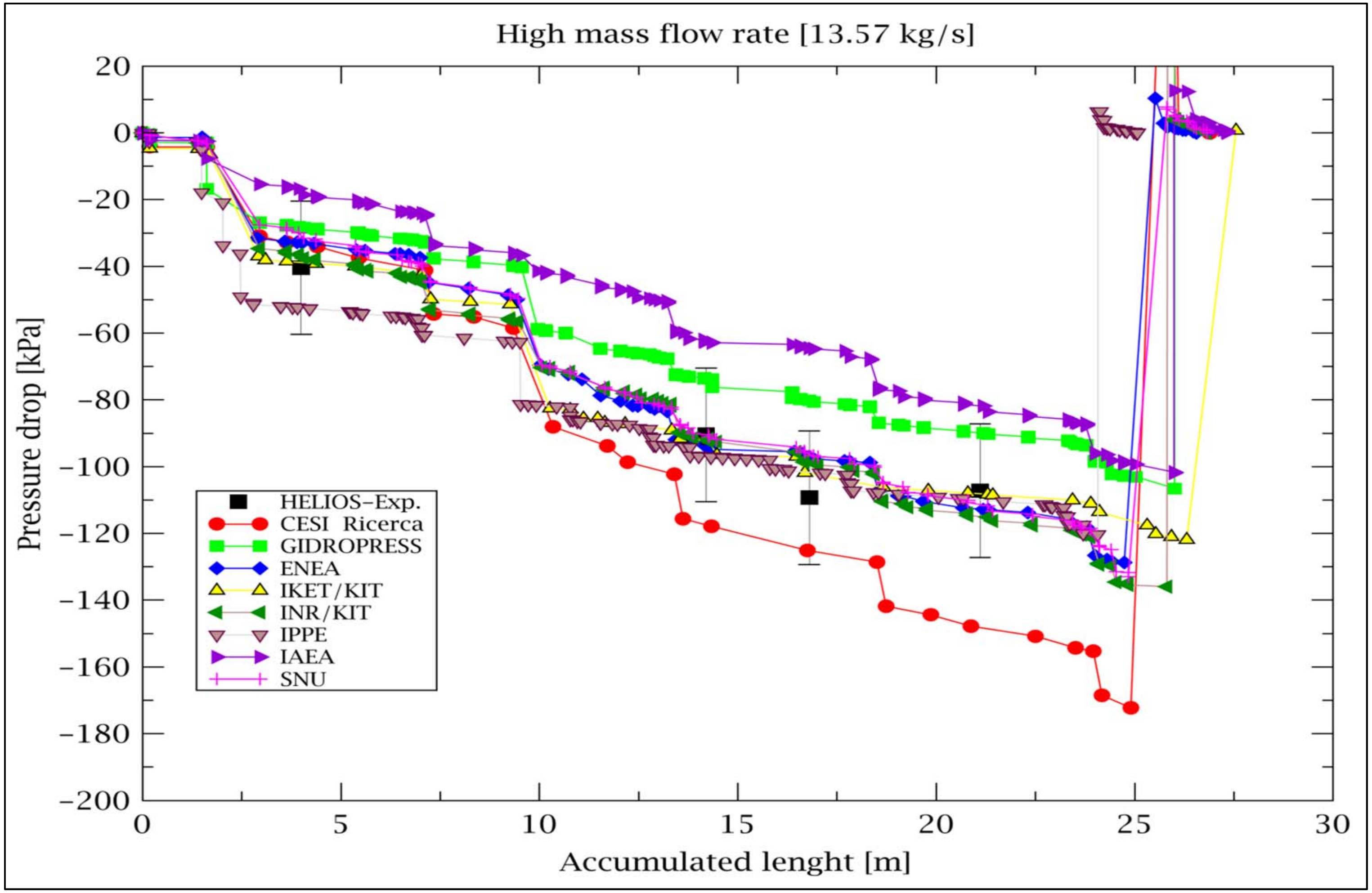
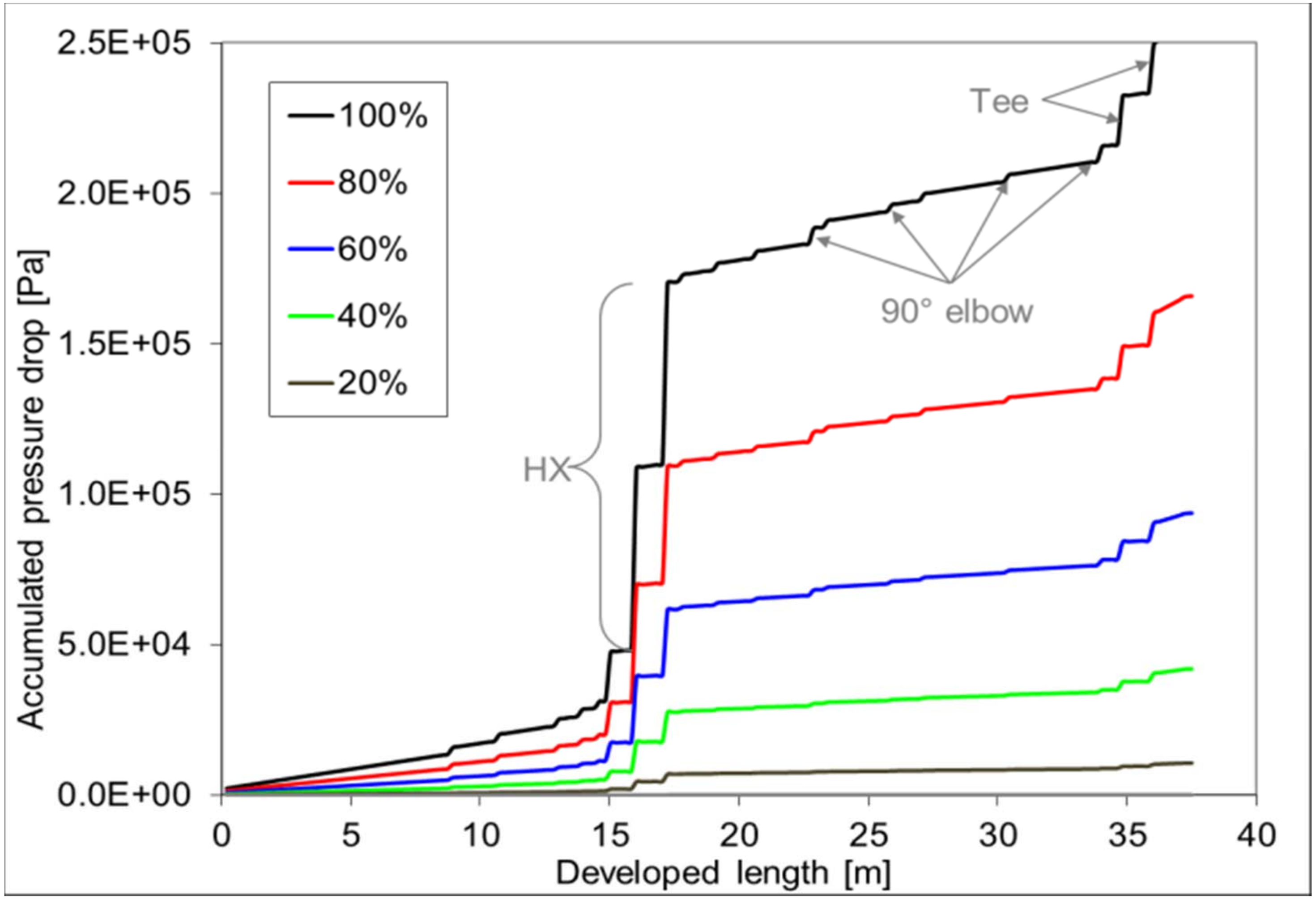
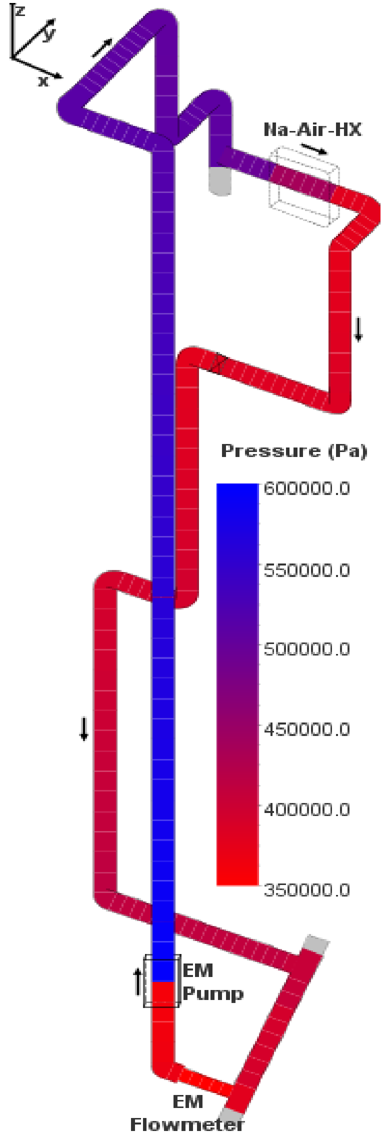
Wall Drag: LACANES Benchmark 2/2



Jaeger, W. & Sánchez Espinoza, V.H., "Improvements and Validation of the System Code TRACE for Lead and Lead-Alloy Cooled Fast Reactors Safety-Related Investigations.", *NUREG/IA-0421*. Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC.

Wall Drag: KASOLA 1/2





Jaeger, W., Homann, Ch., Hering, W. & Jammot, V., "Preparation of KASOLA Scientific Work Program using TRACE.", *International Congress on Advances in Nuclear Power Plants (ICAPP2014)*. Charlotte, U.S.A., 2014.

Wall Drag: KASOLA 2/2

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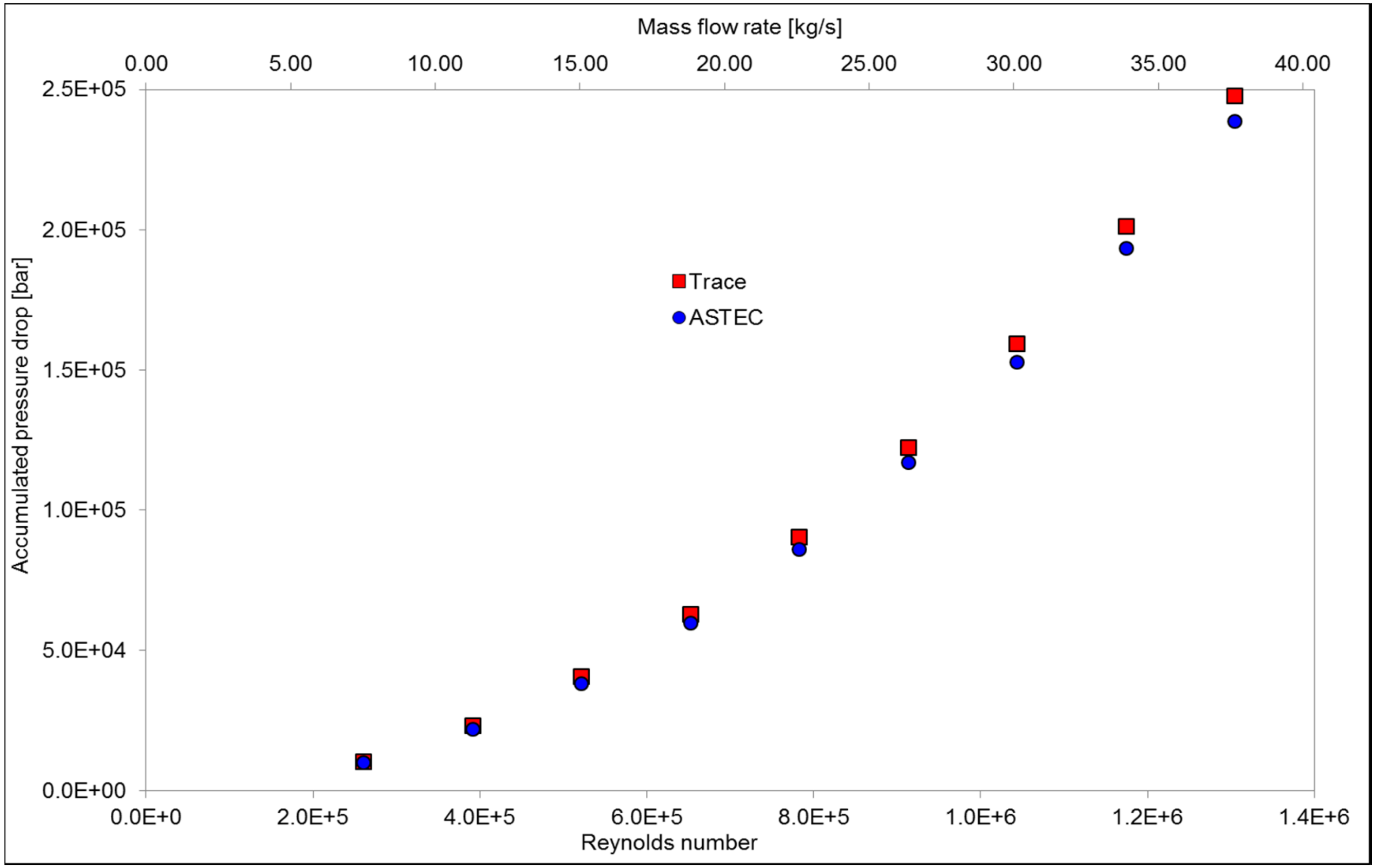
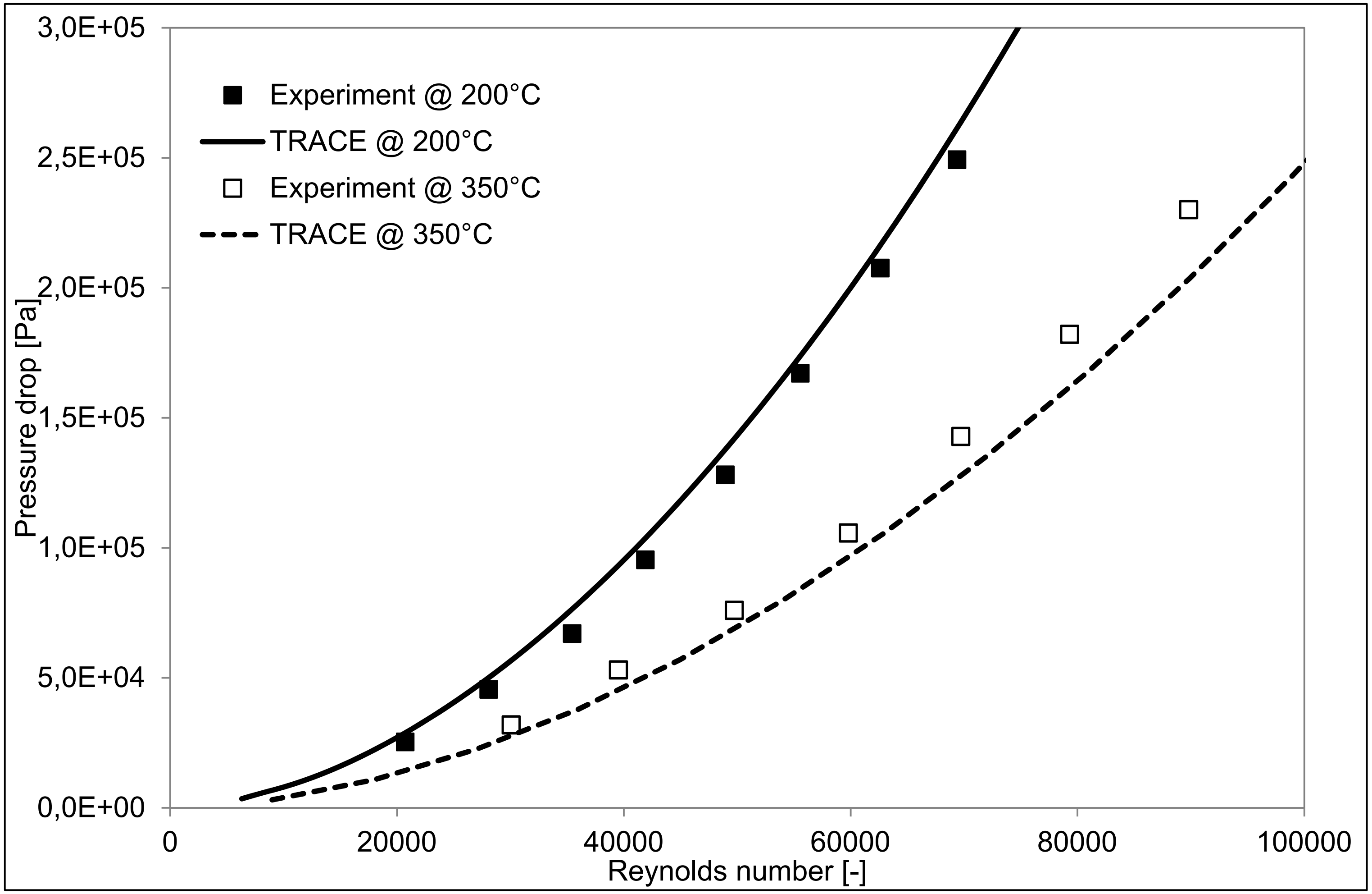
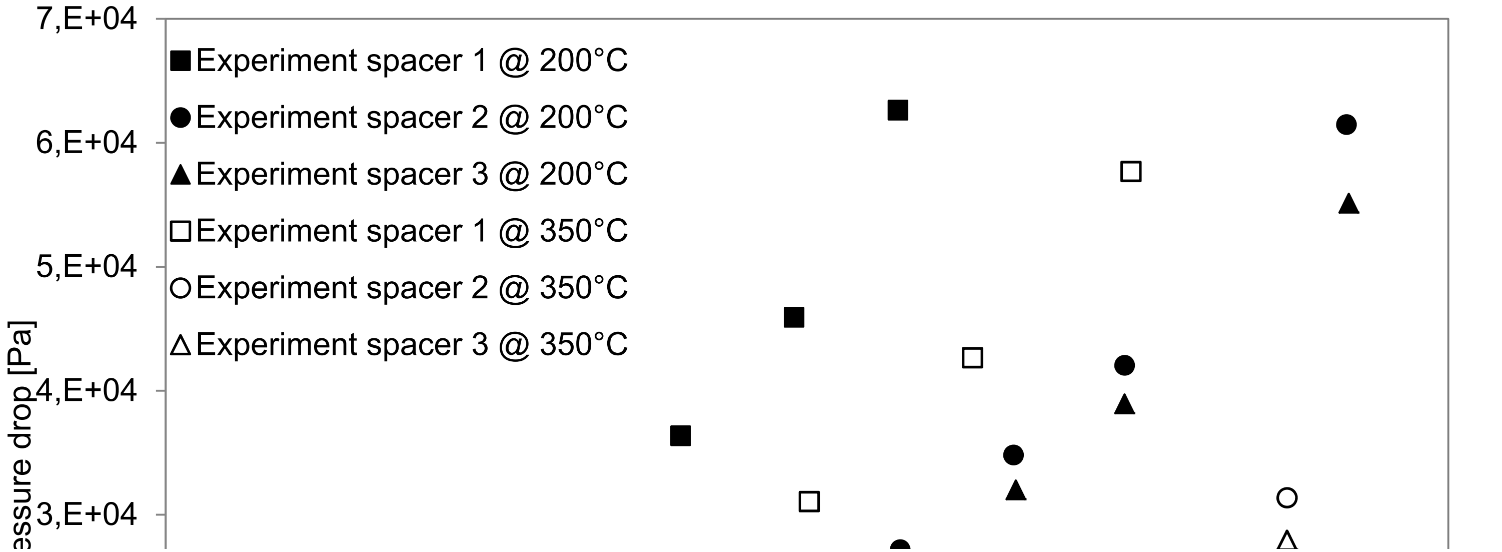


Wall Drag: KALLA Rod Bundle – Bundle



Jaeger, W., Boettcher, M. & Sánchez Espinoza, V.H., "Thermal-Hydraulic Evaluation of an LBE Cooled 19 Pin Bundle in the Frame of TRACE Validation.", *International Conference on Nuclear Engineering (ICONE21)*. Chengdu, China, 2013.

Wall Drag: KALLA Rod Bundle – Spacers (1/2)

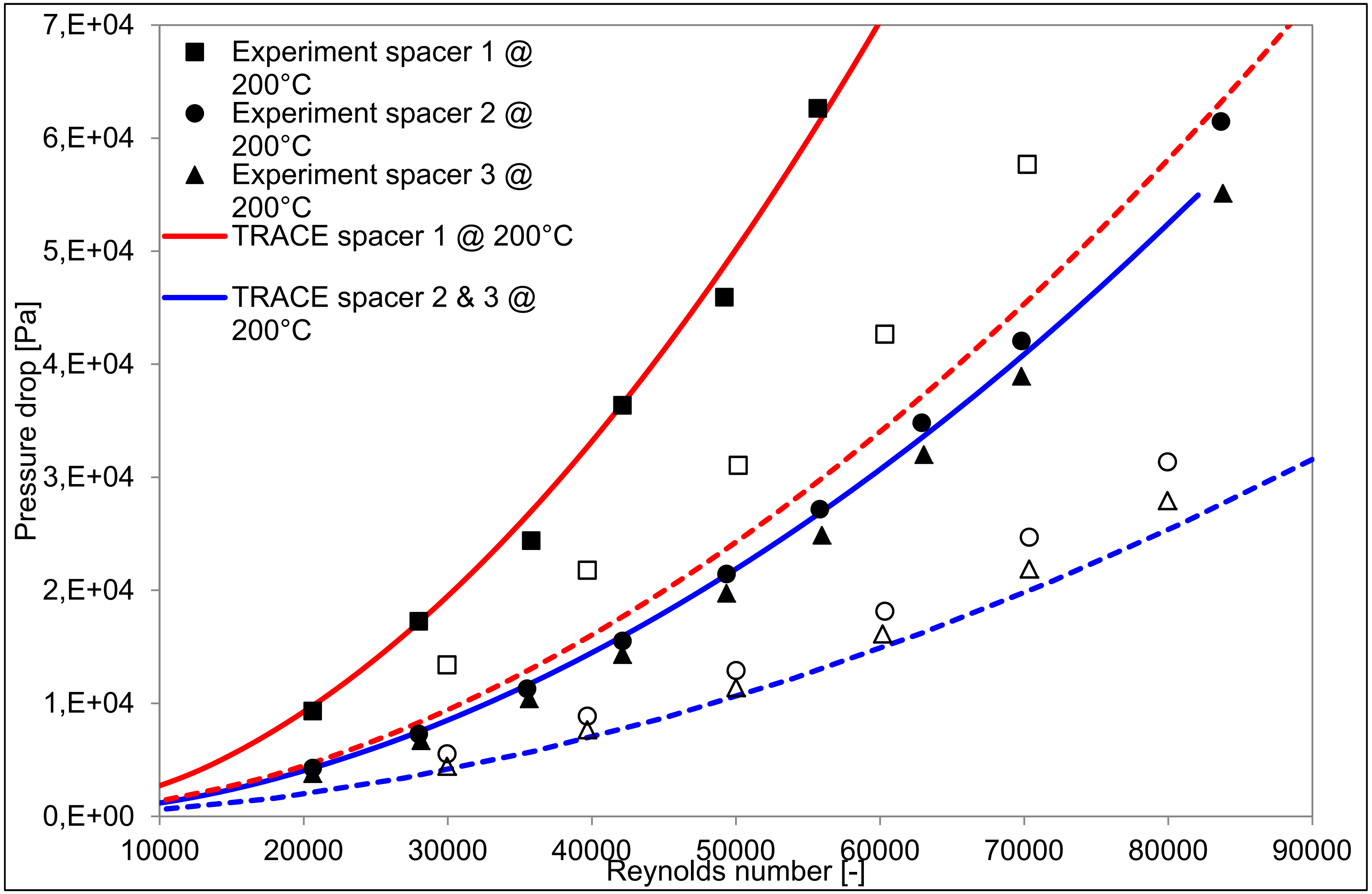


Spacer 1 causes much higher pressure drops than spacers 2 & 3. From the theoretical point of view it seems to be impossible since the thermodynamic and fluid dynamic properties are identical at all three elevations.

The reason for the higher pressure drop might be a plugging of the first spacer with oxidation products increasing the blockage ratio from originally 0.46 to roughly 0.70.

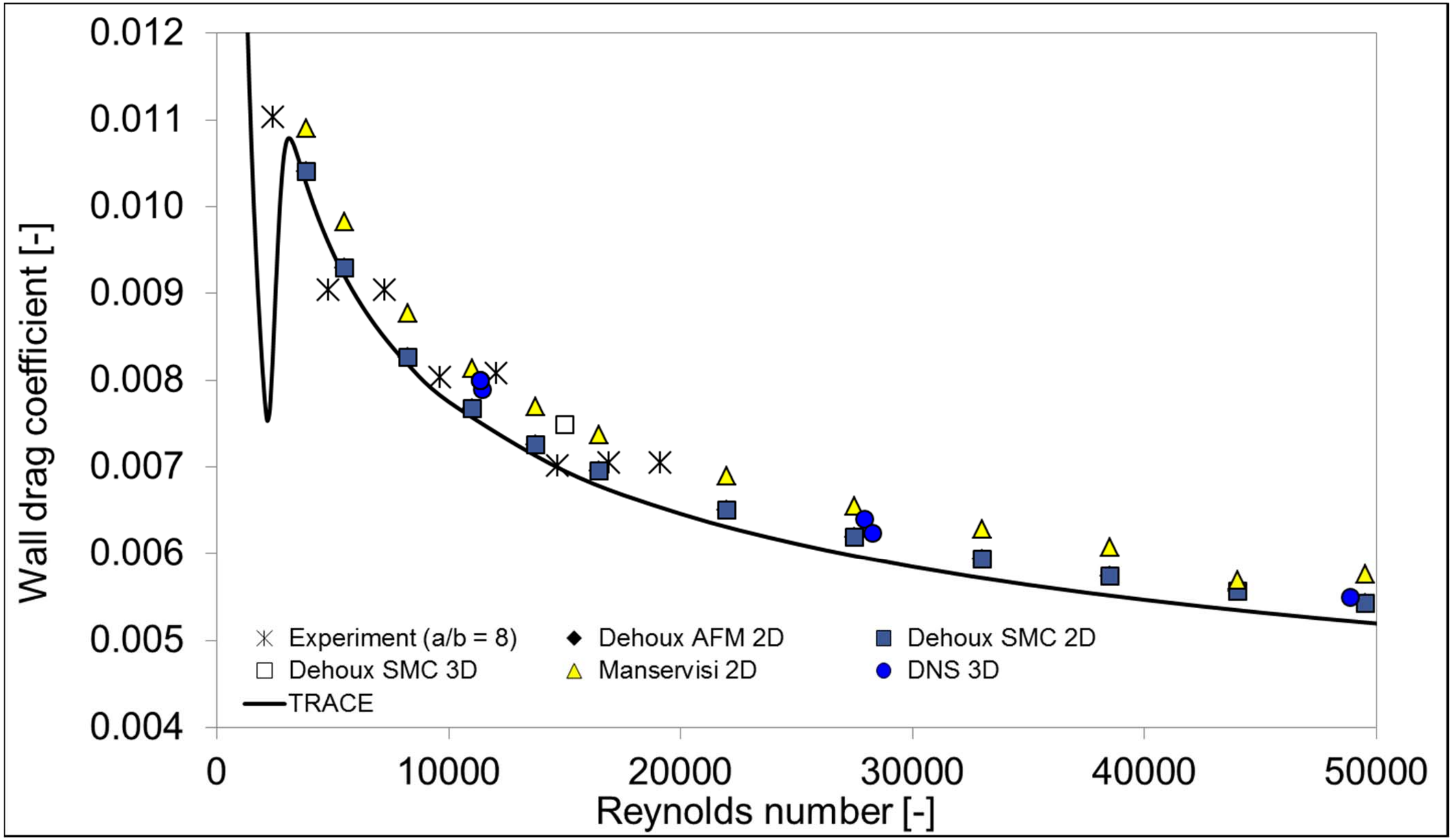
Jaeger, W., Boettcher, M. & Sánchez Espinoza, V.H., "Thermal-Hydraulic Evaluation of an LBE Cooled 19 Pin Bundle in the Frame of TRACE Validation.", *International Conference on Nuclear Engineering (ICONE21)*. Chengdu, China, 2013.

Wall Drag: KALLA Rod Bundle – Spacers (2/2)



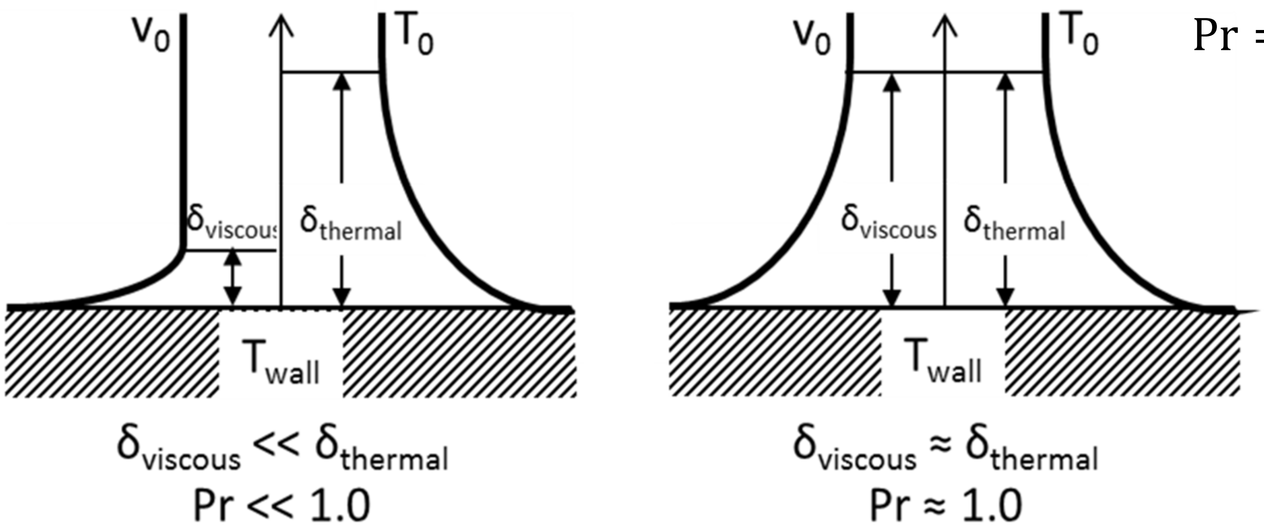
Jaeger, W., Boettcher, M. & Sánchez Espinoza, V.H., "Thermal-Hydraulic Evaluation of an LBE Cooled 19 Pin Bundle in the Frame of TRACE Validation.", *International Conference on Nuclear Engineering (ICONE21)*. Chengdu, China, 2013.

Wall Drag: Rectangular Channels



Liquid Metal Heat Transfer

- Heat transfer to liquid metal ≠ Heat transfer to water.
- Characterization of heat transfer ➔ Prandtl number.
- Prandtl number = Ratio of the momentum and thermal diffusivity.
- Pr ≈ 1 ➔ Thermal boundary layer ≈ Velocity boundary layer.
- Liquid metals ➔ Pr << 1
  - Thermal boundary layer >> Velocity boundary layer
  - Heat diffusion >> Momentum diffusion.
  - Heat conduction >> Heat convection.



$$Pr = \frac{\eta \cdot cp}{k}$$

Na: Pr ≈ 0.006
Pb: Pr ≈ 0.02
Air: Pr ≈ 0.71
H_2O: Pr ≈ 7.0

R. Stieglitz, “Low Prandtl Number Thermal-Hydraulics“, In “Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, OECD/NEA, NEA No. 6195, 2007.

Liquid Metal Heat Transfer – Regimes

Flow Regime/Phenomena		Duct Flow			Bundle Flow	
		○	□	◎	△	□
Forced convection	Laminar	X				
	Turbulent	X				
	Transition	X				
Mixed convection	Laminar					
	Turbulent					
	Transition					
Free convection	Laminar					
	Turbulent					
	Transition					
Entrance Length Effect						
Variable Property Effect						

Original version

Liquid Metal Heat Transfer – Regimes

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<table>
<tr><th colspan="2" rowspan="2">Flow Regime/Phenomena</th><th colspan="3">Duct Flow</th><th colspan="2">Bundle Flow</th></tr>
<tr><th>○</th><th>□</th><th>◎</th><th>△</th><th>□</th></tr>
<tr><td rowspan="3">Forced convection</td><td>Laminar</td><td>X</td><td>X</td><td>X</td><td colspan="2">X</td></tr>
<tr><td>Turbulent</td><td>X</td><td>X</td><td>X</td><td colspan="2">X</td></tr>
<tr><td>Transition</td><td>X</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="3">Mixed convection</td><td>Laminar</td><td>X</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Turbulent</td><td>X</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Transition</td><td>X</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="3">Free convection</td><td>Laminar</td><td>-</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Turbulent</td><td>X</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Transition</td><td>-</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="2">Entrance Length Effect</td><td>X</td><td></td><td></td><td colspan="2">X</td></tr>
<tr><td colspan="2">Variable Property Effect</td><td></td><td></td><td></td><td colspan="2"></td></tr>
</table>

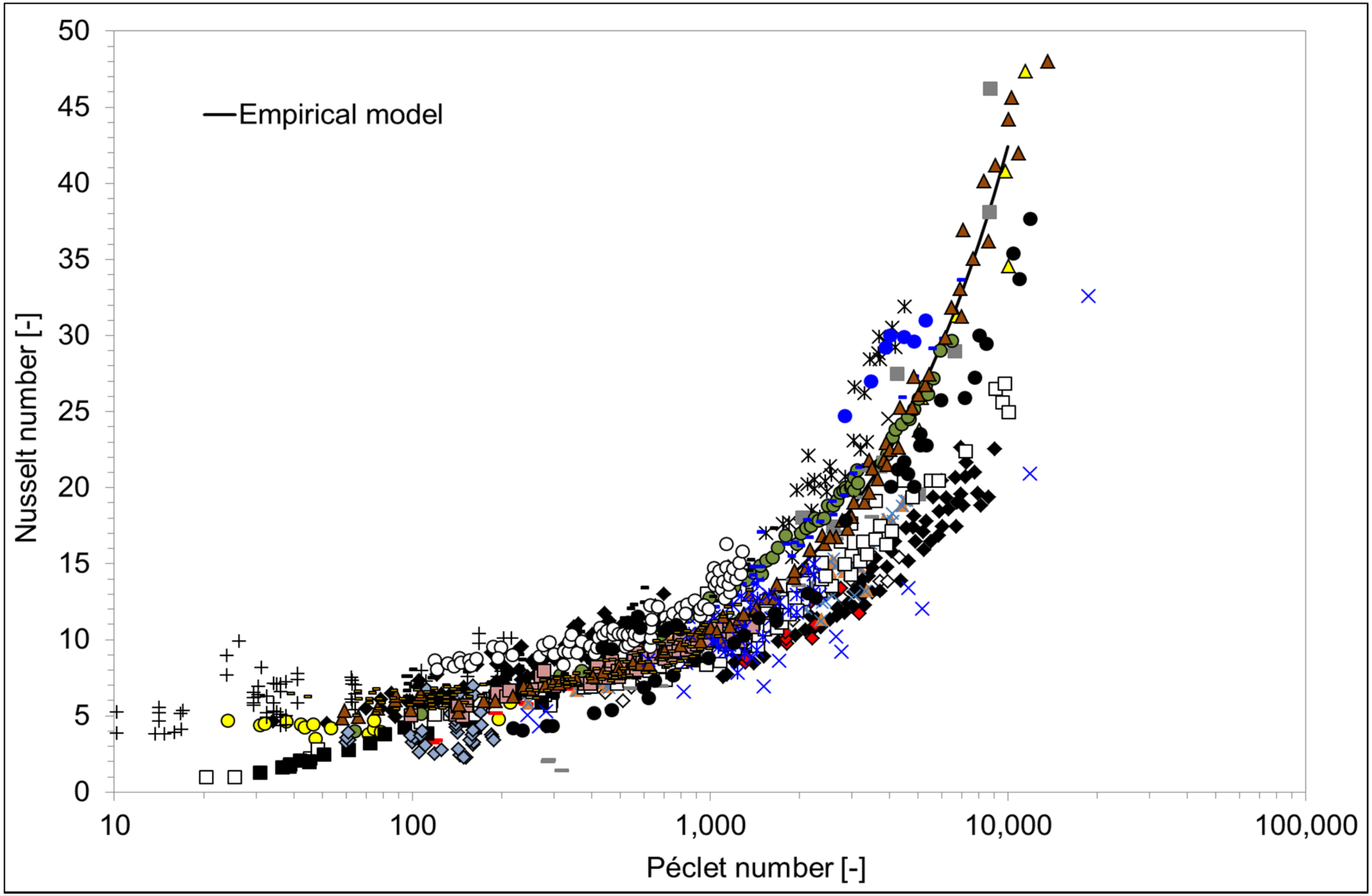
Modified version

Liquid Metal Heat Transfer – Models

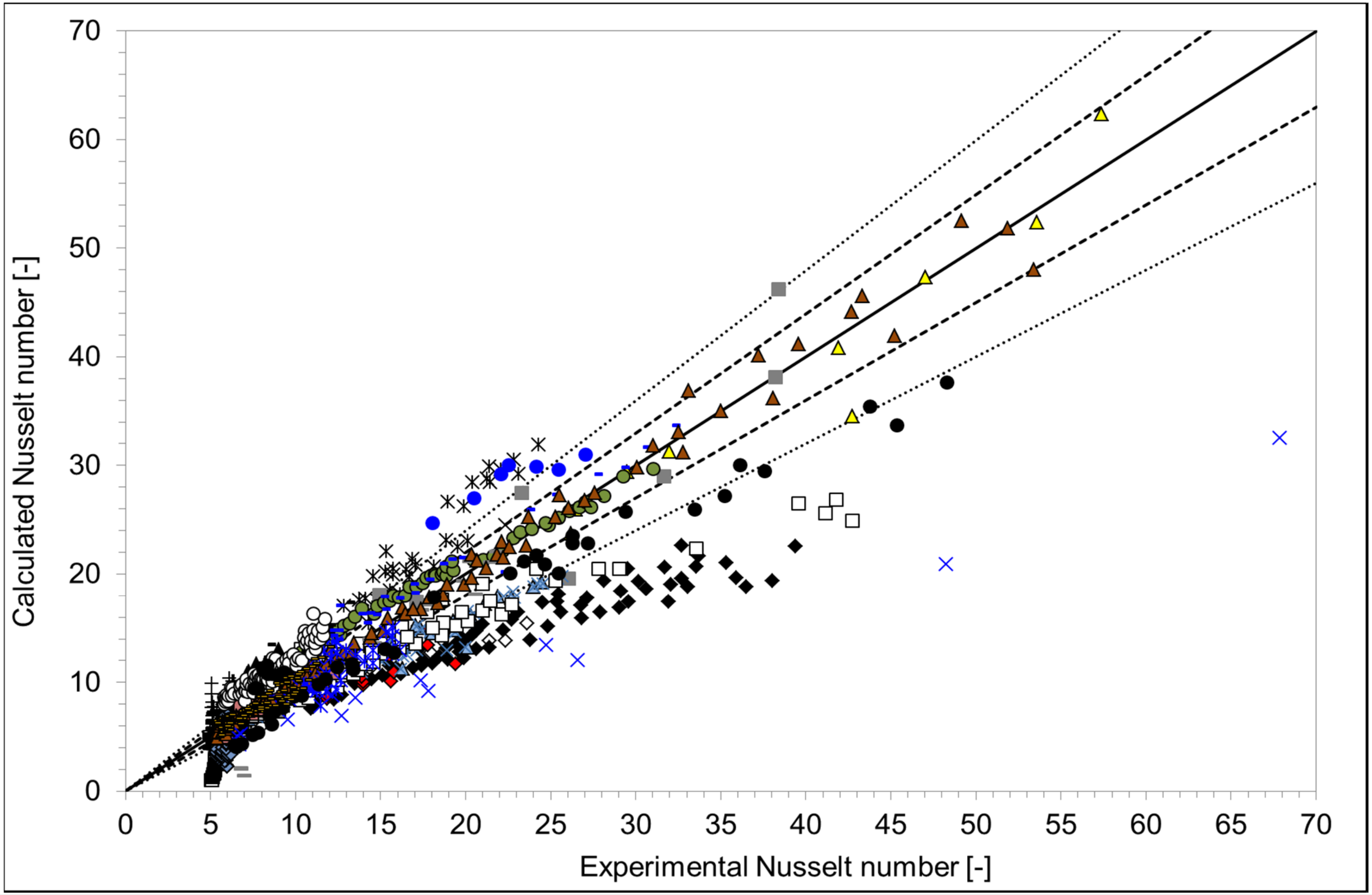
Flow Regime/Phenomena		Duct Flow			Bundle Flow	
		○	□	◎	△	□
Forced convection	Laminar	Const.	Jaeger	Jaeger	Const.	
	Turbulent	Stupinski	Jaeger	Jaeger	Ushakov	
	Transition	Stupinski			Ushakov	
Mixed convection	Laminar	Cubic				
	Turbulent	Cubic				
	Transition	Cubic				
Free convection	Laminar					
	Turbulent	Hyman				
	Transition					
Entrance Length Effect		Das			Jaeger	
Variable Property Effect						

Modified version

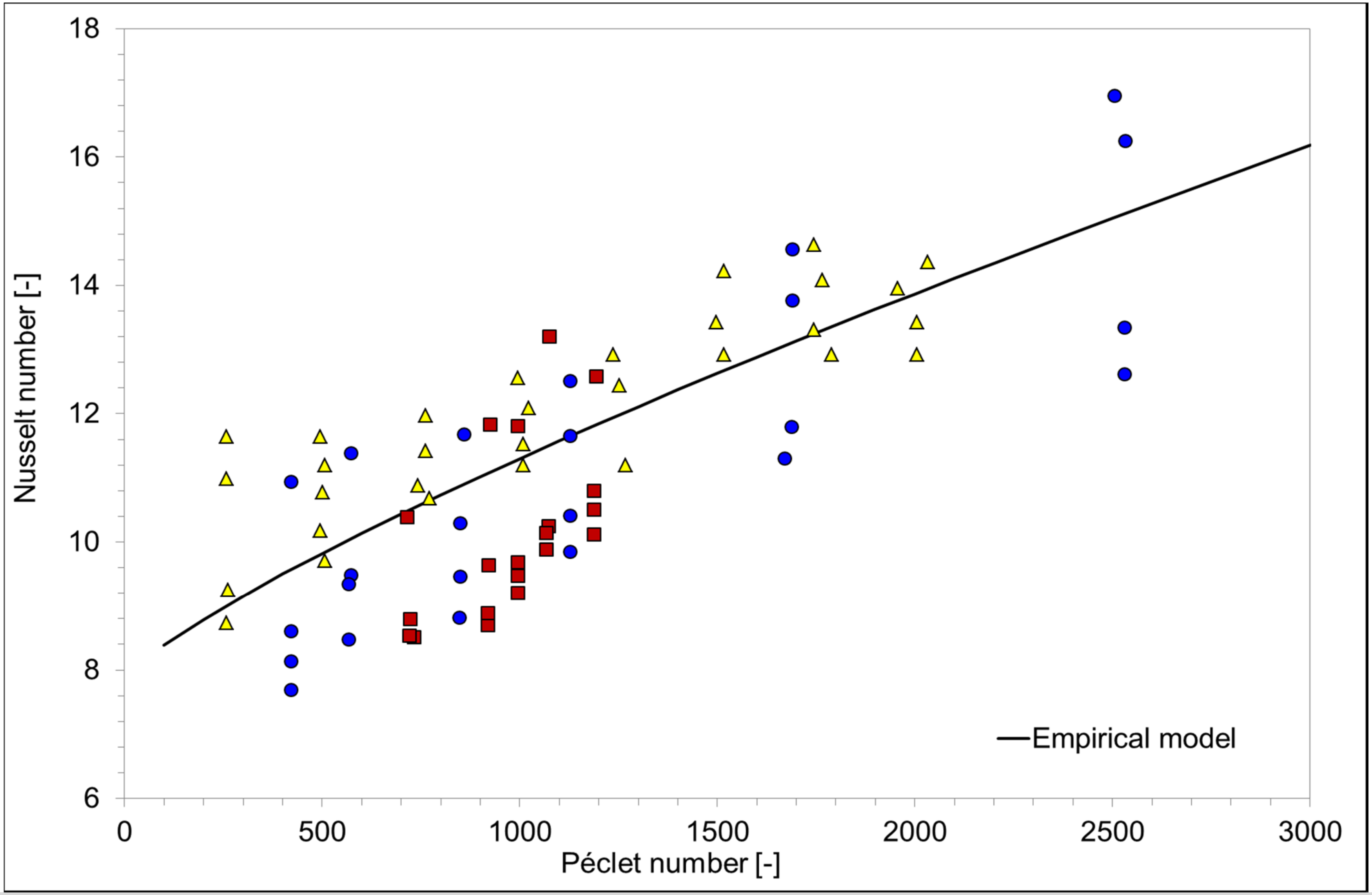
Liquid Metal Heat Transfer – Pipe



Liquid Metal Heat Transfer – Pipe



Liquid Metal Heat Transfer – Rectangular



Liquid Metal Heat Transfer – Rectangular

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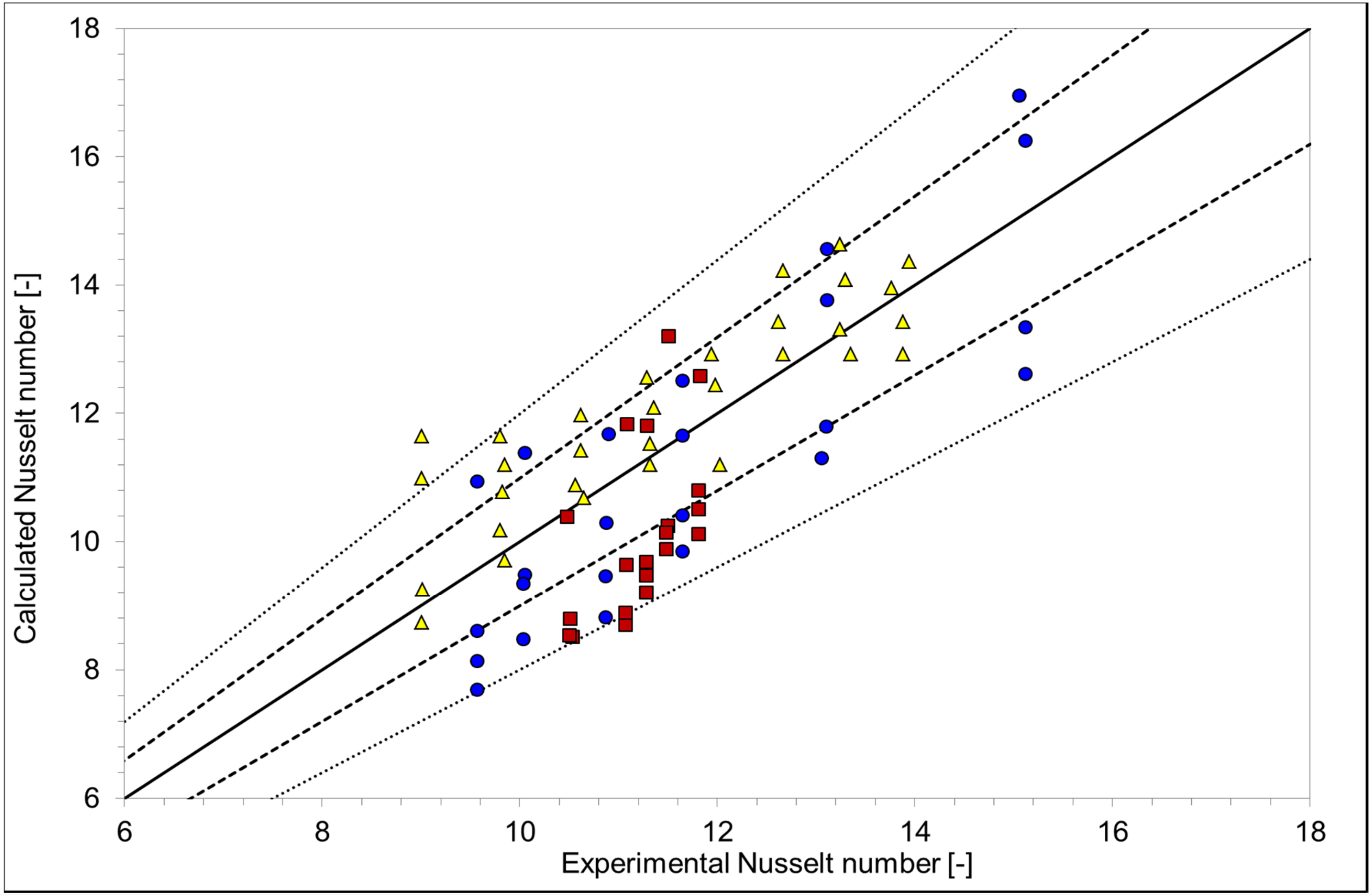
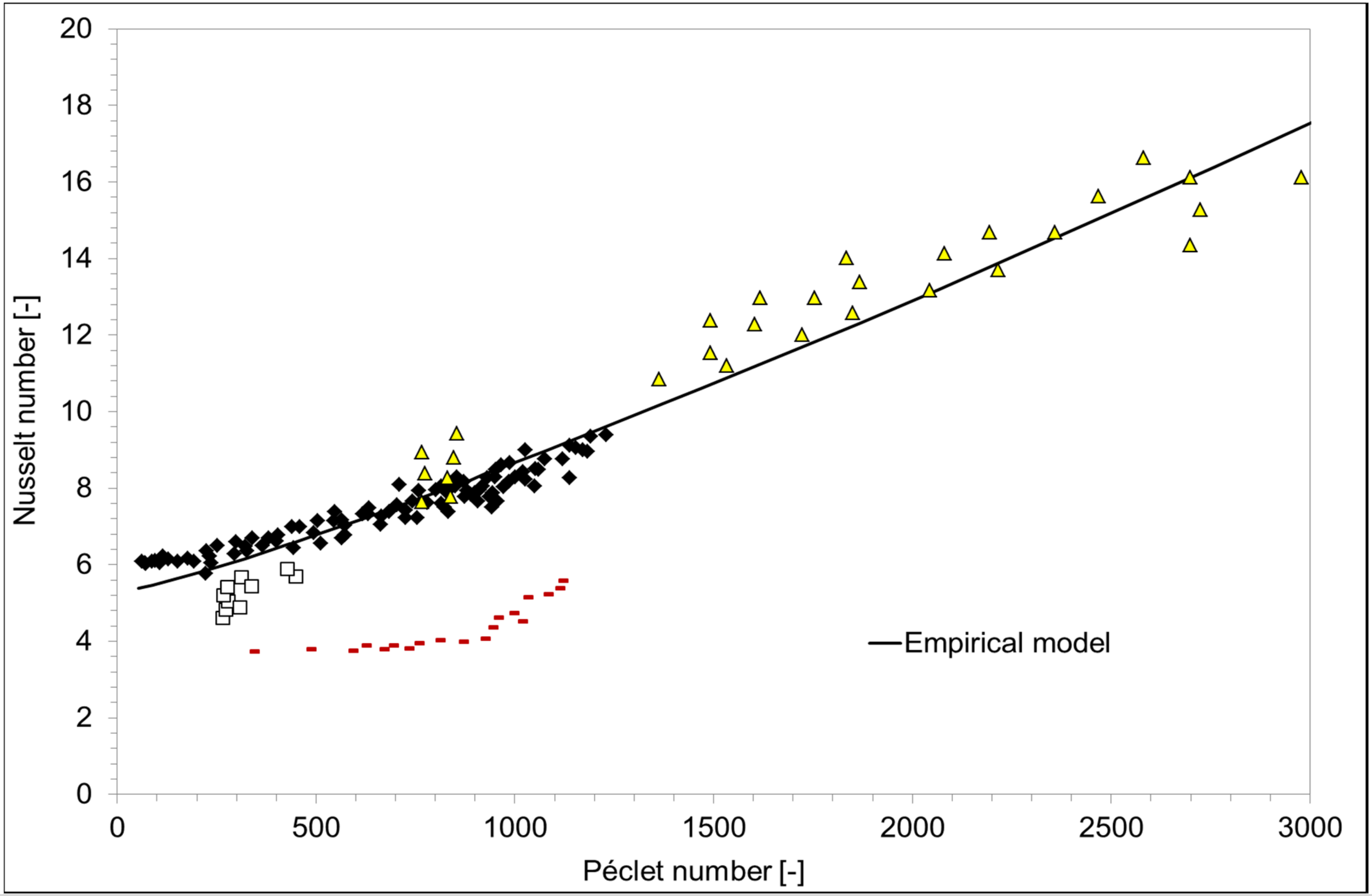
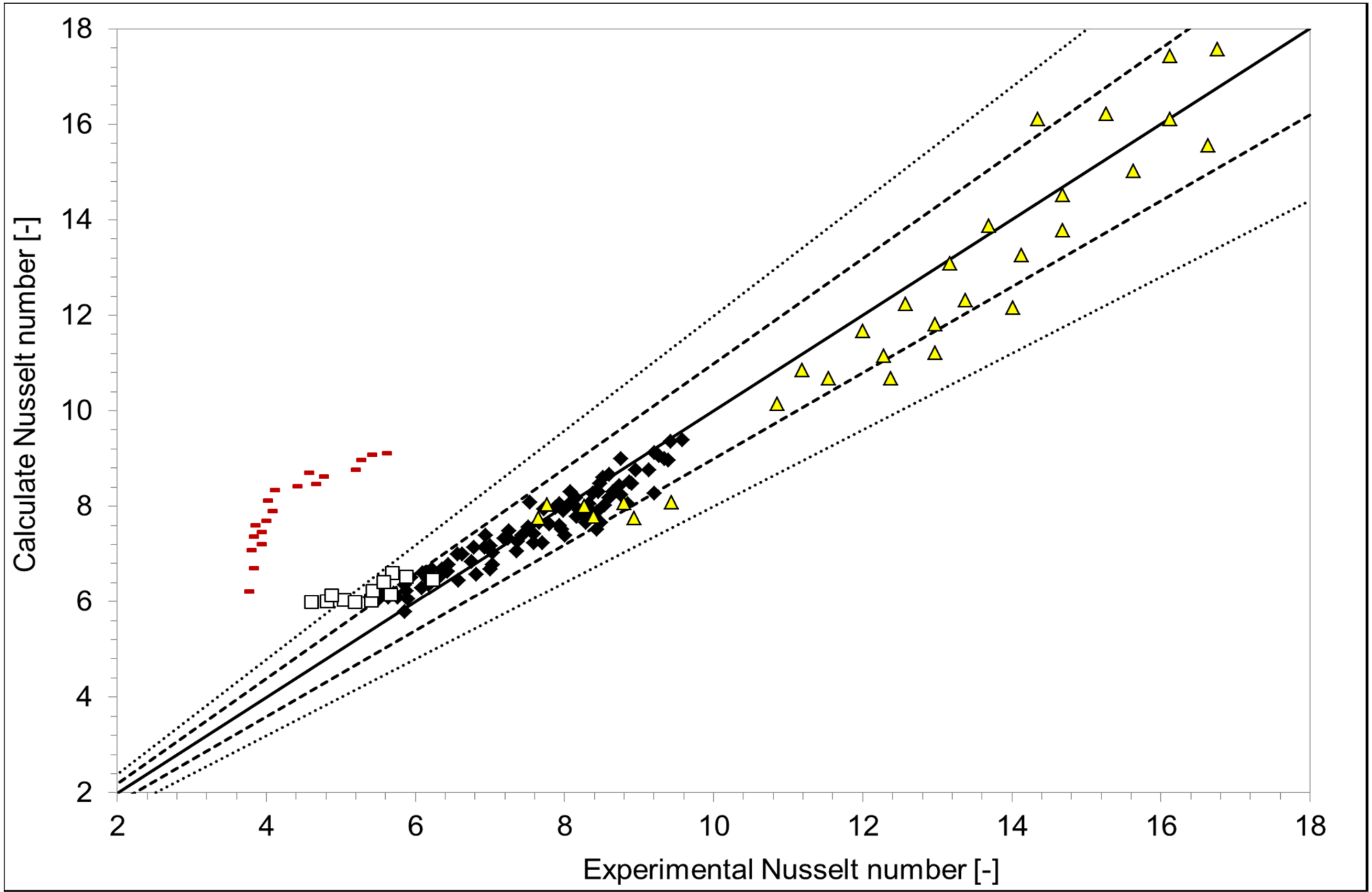


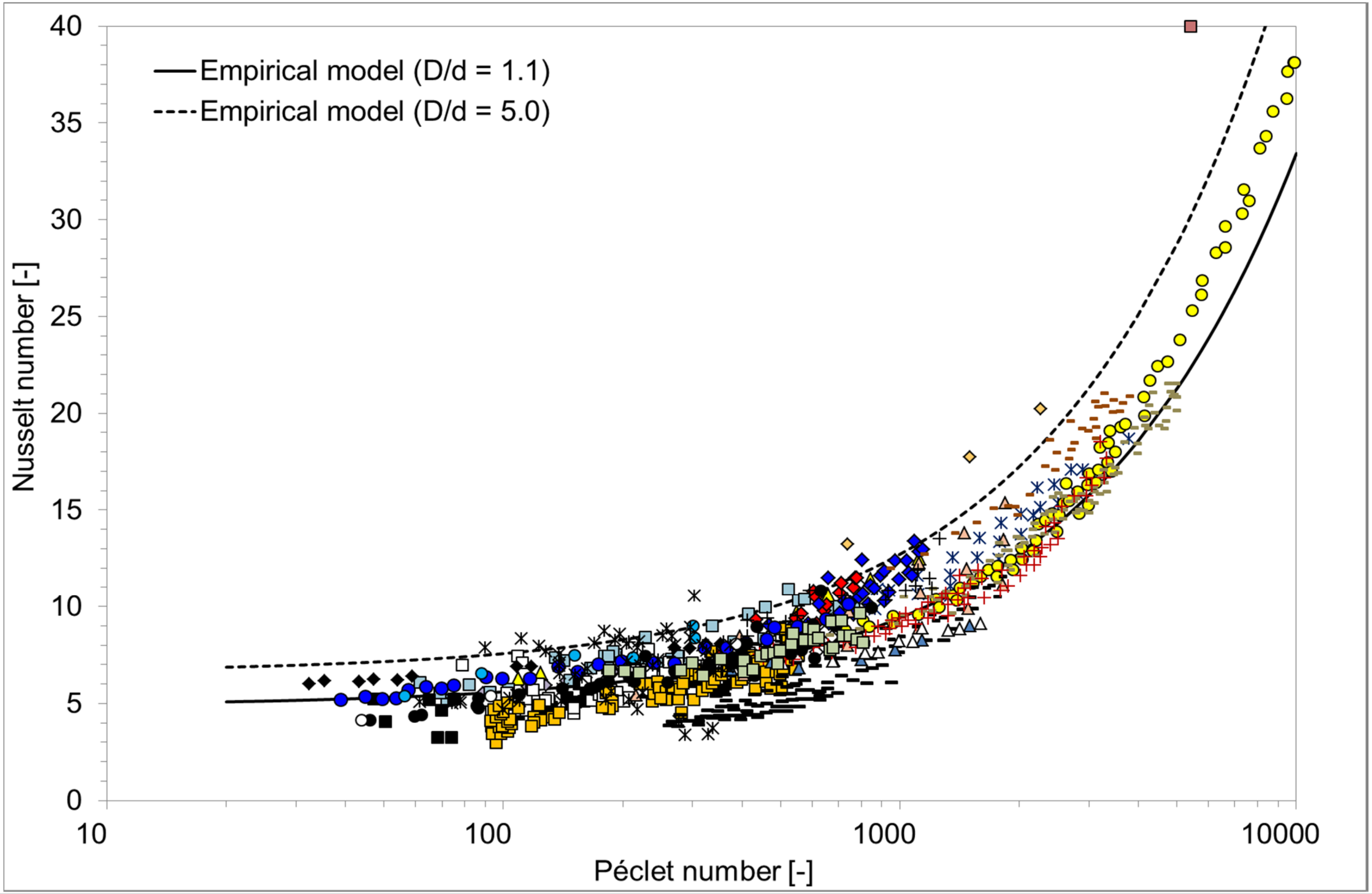
Liquid Metal Heat Transfer – Parallel Plate



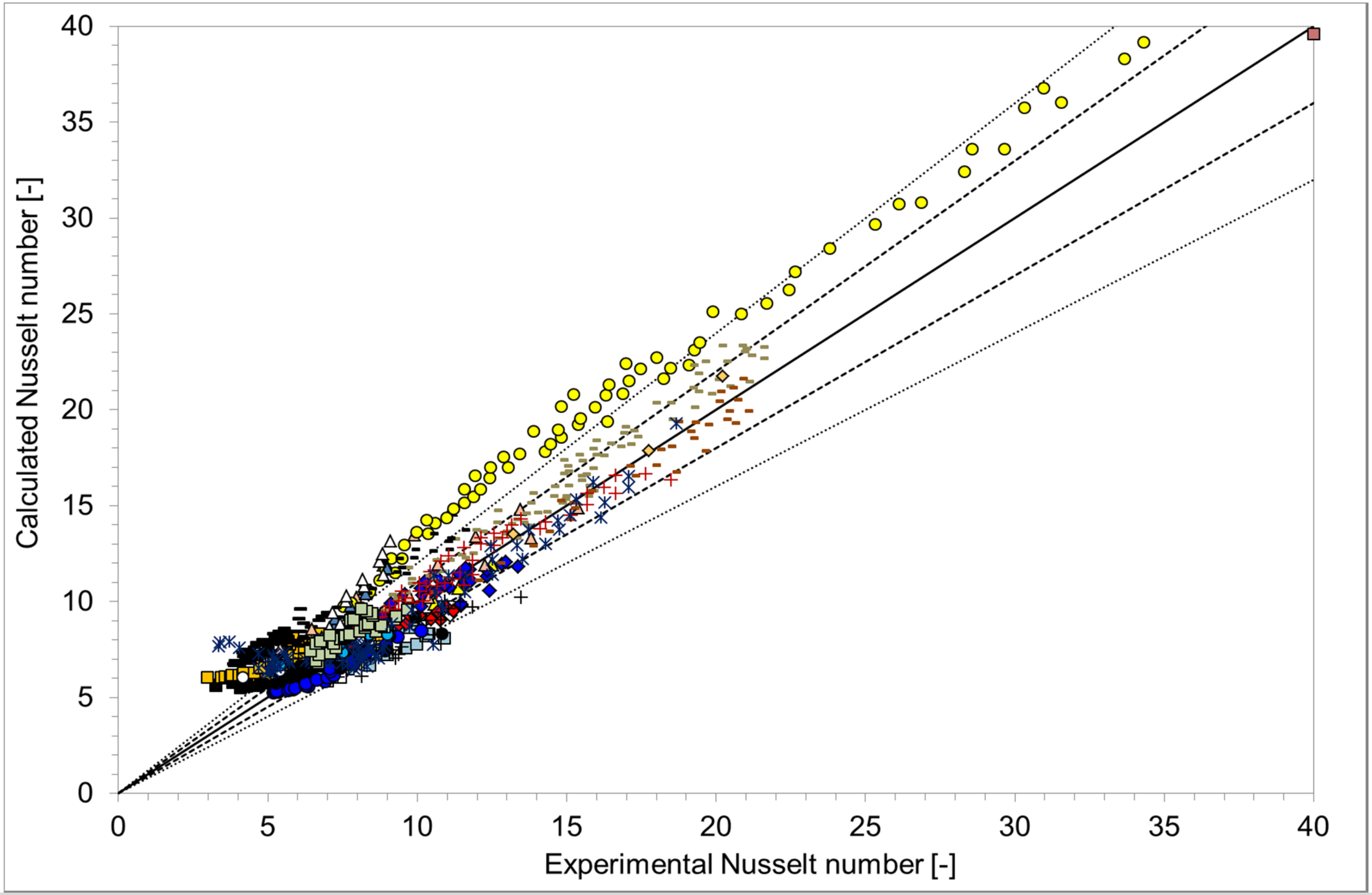
Liquid Metal Heat Transfer – Parallel Plate



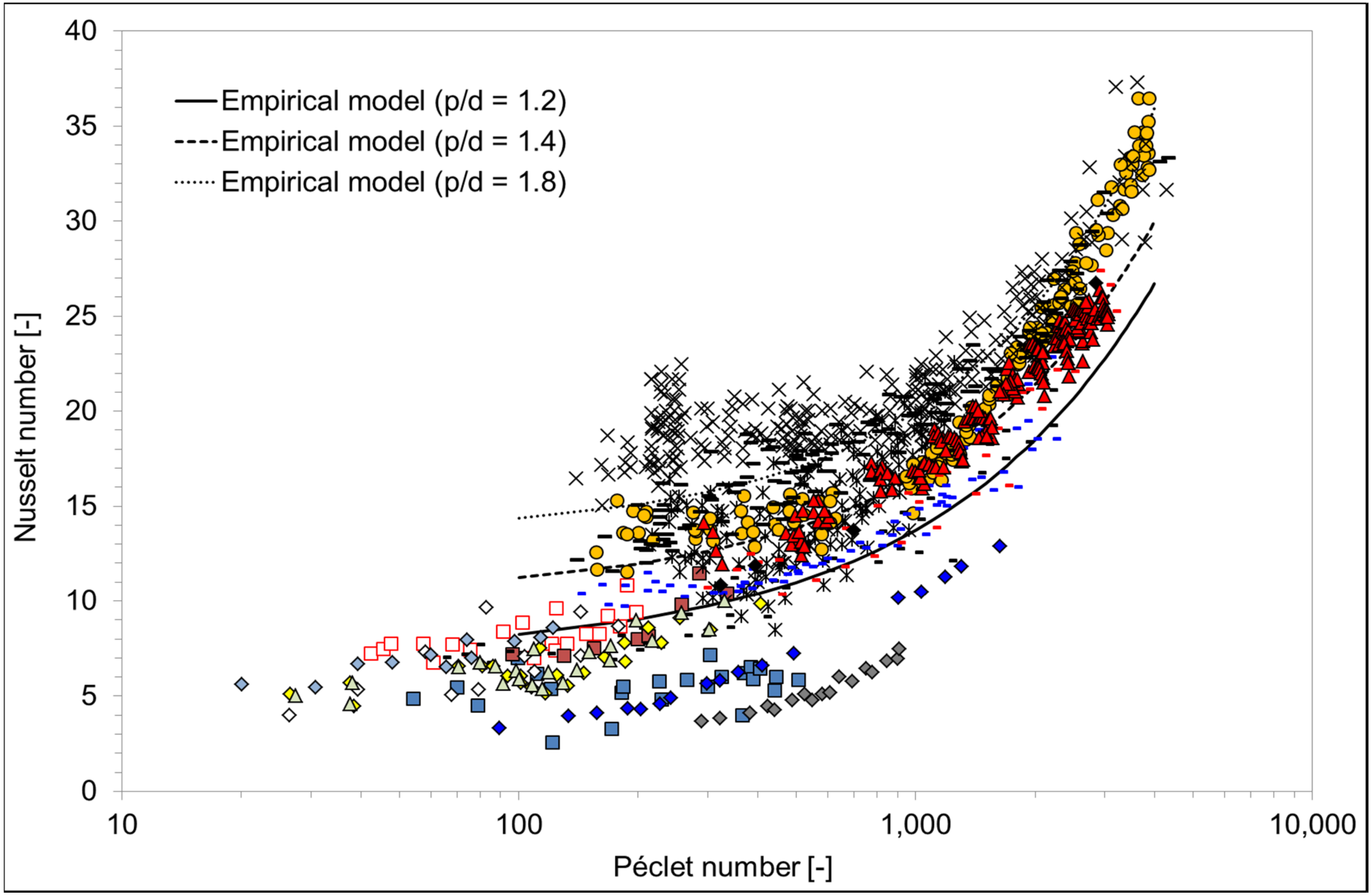
Liquid Metal Heat Transfer – Annular



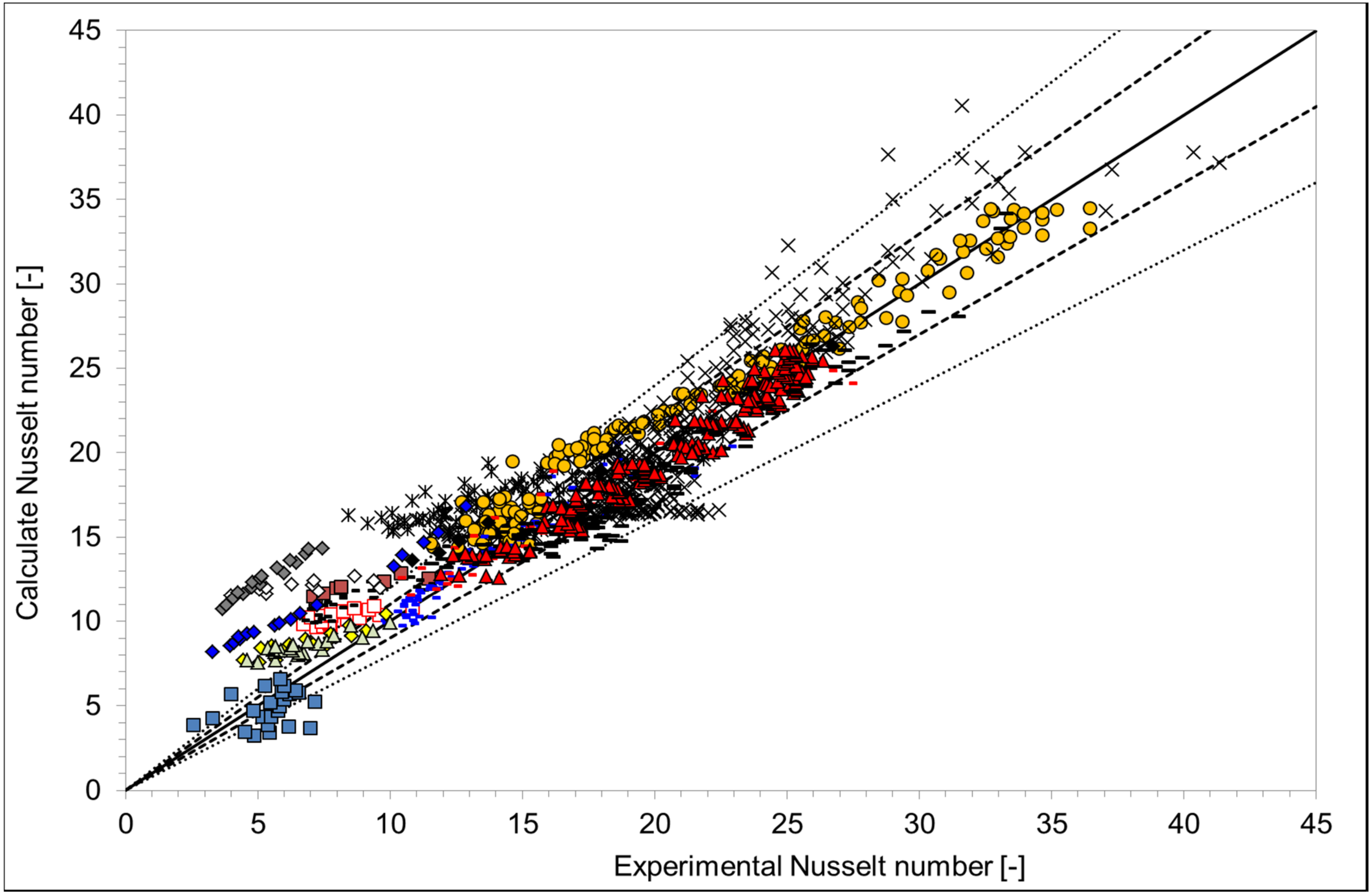
Liquid Metal Heat Transfer – Annular



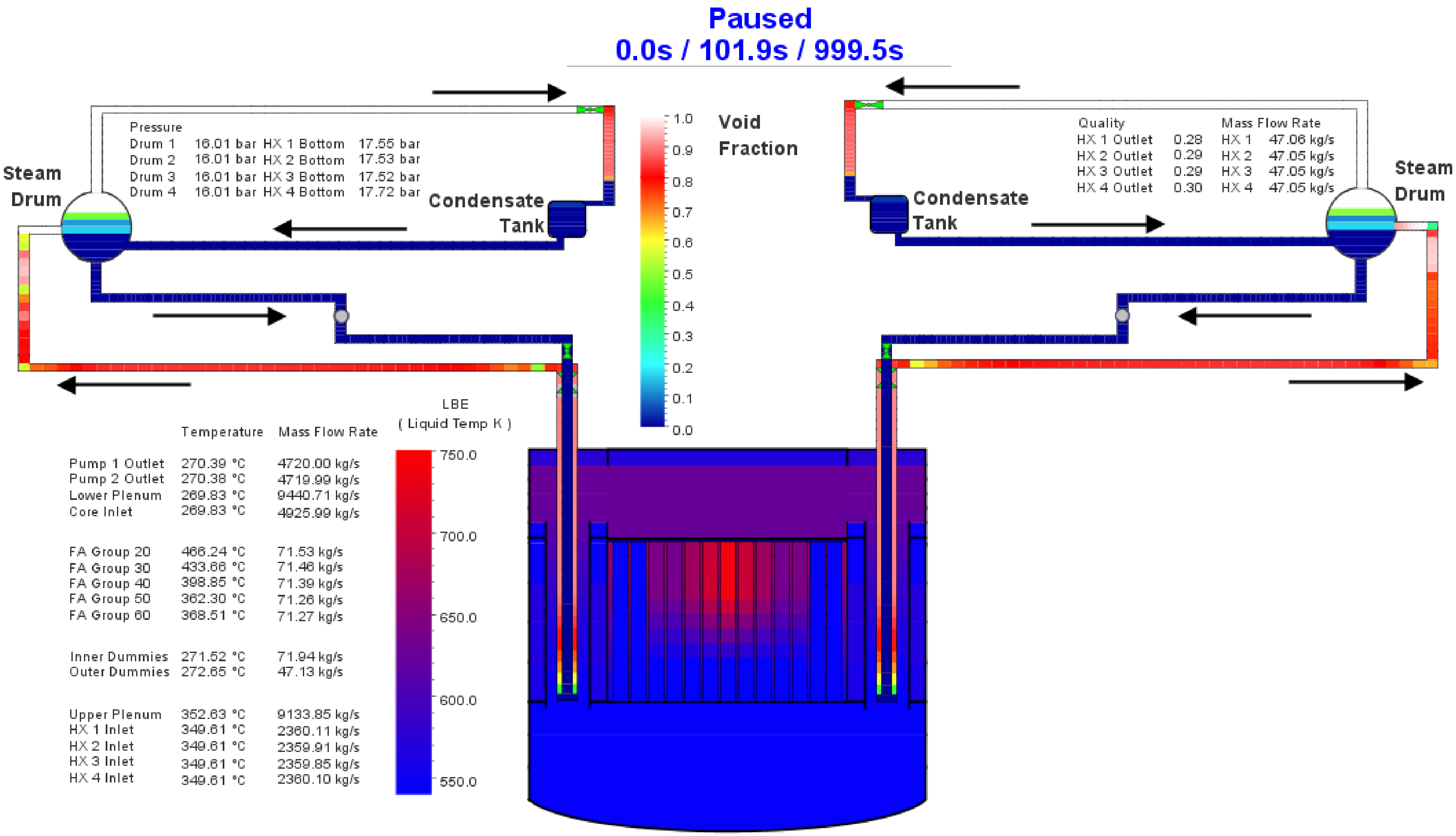
Liquid Metal Heat Transfer – Rod Bundle



Liquid Metal Heat Transfer – Rod Bundle



Liquid Metal Heat Transfer – Application



Summary & Conclusion

Review → Development → Validation → Application

- Empirical (system code) and turbulent Prandtl number look-up tables (CFD) developed for forced convection flows of liquid metals
- Validation process shows good agreement to reference data
- Easy to implement in other system codes and CFD codes

➔ More experimental data and DNS/LES data are required to continue the validation process for mixed and natural convection flows