Recent work and developments for Code_Satune

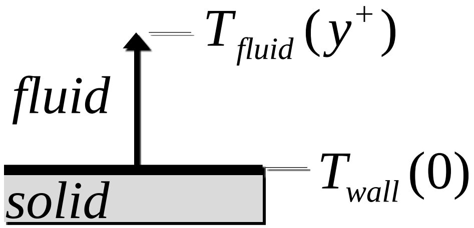
Richard Howard
9th April 2013

- **A wall model for conjugate gradient heat transfer**
- Evaluation of an inverse method for calculating the wall heat flux
- LES on non-structured grids
- A practical example of non-structured simulations in complex geometries

Background: thermal flux at the wall

$$\varphi = (\lambda + \lambda_t) \left. \frac{\partial T}{\partial y} \right|_{wall}$$

$$\varphi = \rho c_p (u_* T^*) \qquad \varphi = h(y^+) \Delta T(y^+)$$



with $T^+(y^+) = \dfrac{\Delta T(y^+)}{T^*}$ and $\Delta T(y^+) = T_{fluid}(y^+) - T_{wall}(0)$

so $h(y^+) = \dfrac{\rho c_p u_*}{T^+(y^+)}$

an empirical function is used to get the temperature $T^+ = f(y^+)$

Background: example functions

The Kader (1981) function

$$T^+ = \Pr \enclose{circle}{y^+ e}^{-L} + \left(2.12 ln\left(1 + \enclose{circle}{y^+}\right) + \beta\right) e^{-1/L}$$

$$\beta = \left(3.85 \Pr^{1/3} - 1.3\right)^2 + 2.12 ln(\Pr)$$

$$L = \left[0.01\left(\Pr \enclose{circle}{y^+}\right)^4\right] / \left[1 + 5 \Pr^3 \enclose{circle}{y^+}\right]$$

Arpaci and Larsen (1984) three layer model

$$T^+ = \begin{cases} \Pr \enclose{circle}{y^+} \Rightarrow y^+ < y_1^{\ +} \\ a_2 - \dfrac{\Pr_t}{2a_1 \enclose{circle}{y^{+2}}} \Rightarrow y_1^{\ +} \le y^+ \le y_2^{\ +} \\ \dfrac{\Pr_t}{\kappa} ln\left(\enclose{circle}{y^+}\right) + a_3 \Rightarrow y_2^{\ +} \le y^+ \end{cases}$$

$$y_1^{\ +} = (1000 / \Pr)^{1/3}$$

$$y_2^{\ +} = \sqrt{(1000\kappa / \Pr_t)}$$

$$a_1 = \Pr_t / 1000$$

$$a_2 = 15 \Pr^{2/3}$$

$$a_3 = 15 \Pr^{2/3} - \frac{\Pr_t}{2\kappa}\left(1 + ln\left(\frac{1000\kappa}{\Pr_t}\right)\right)$$

New function: include a temperature dependence

Temperature dependent y+ -> replace u* by T*

$$y_T^{\ +} = \frac{y\rho c_p}{\lambda}\frac{uT^*}{T} = \frac{y\rho\,\mathrm{Pr}}{\mu}\frac{uT^*}{T} = \frac{yu^*\rho\,\mathrm{Pr}}{\mu}\frac{uT^*}{u^*T} = y^+\frac{u^+}{T^+}$$

definitions

$$T^* = \frac{\varphi}{\rho c_p u_*} \qquad y^+ = \frac{y\rho u^*}{\mu} \qquad T^+ = \frac{T}{T^*} \qquad \mathrm{Pr} = \frac{c_p\mu}{\lambda}$$

New function: include a temperature dependence

Insert the new y+ in a previous law or make a new law using the Reichardt profile

$$u^+ = \frac{1}{\kappa}\ln\left(1+\kappa y^+\right) + 7.8\left(1 - e^{-y^+/11} - \frac{y^+}{11}e^{-y^+/3}\right)$$

Thermal Reichardt function with temperature dependence

$$y_T^+ = y^+\frac{u^+}{T^+}$$

$$T^+ = \frac{1}{\kappa}\ln\left(1 + \Pr\kappa y^+\left\{\Pr u^+/T^+\right\}^p\right) + \left[\left(\sqrt{7.8}+1.3\right)A - 1.3\right]^2\left(1 - e^{-By_T^+/11} - \frac{Cy_T^+}{11}e^{-Dy_T^+/3}\right)$$

$$A = \Pr^{0.29} \qquad B = \Pr^{0.4} \qquad C = \Pr^{0.2} \qquad D = \Pr^{0.4} \qquad p = e^{-0.1/\Pr^2}$$

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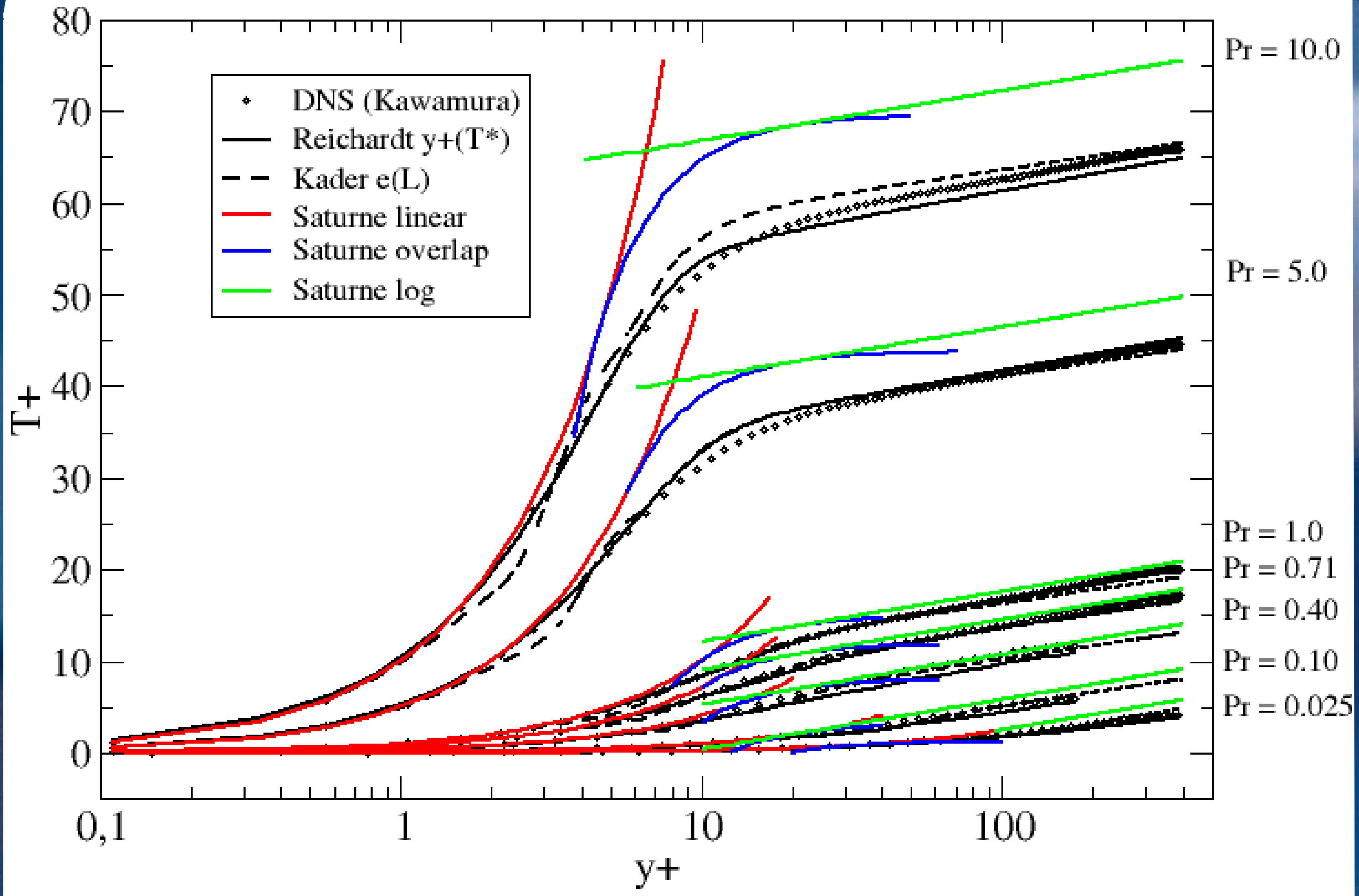
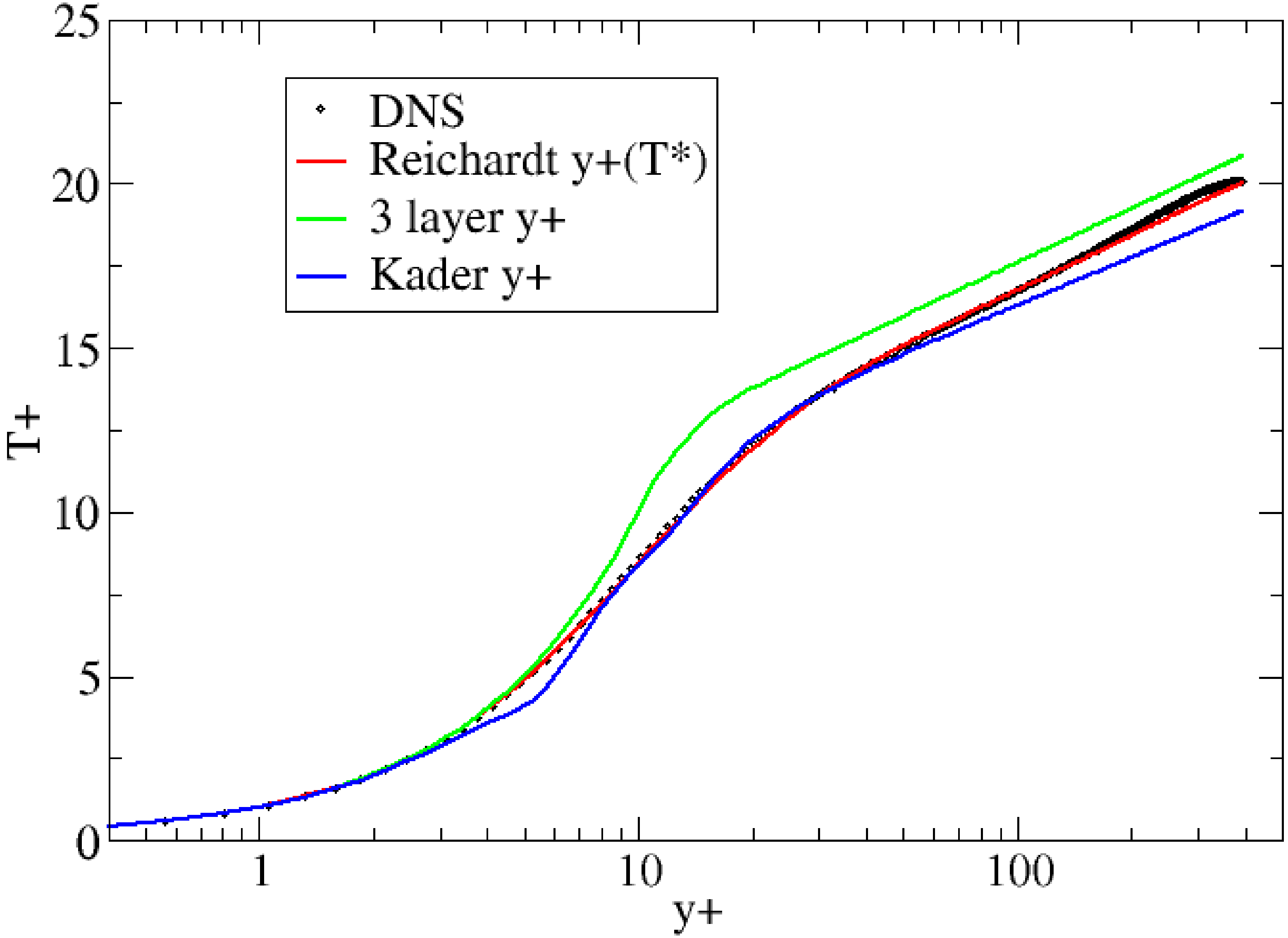
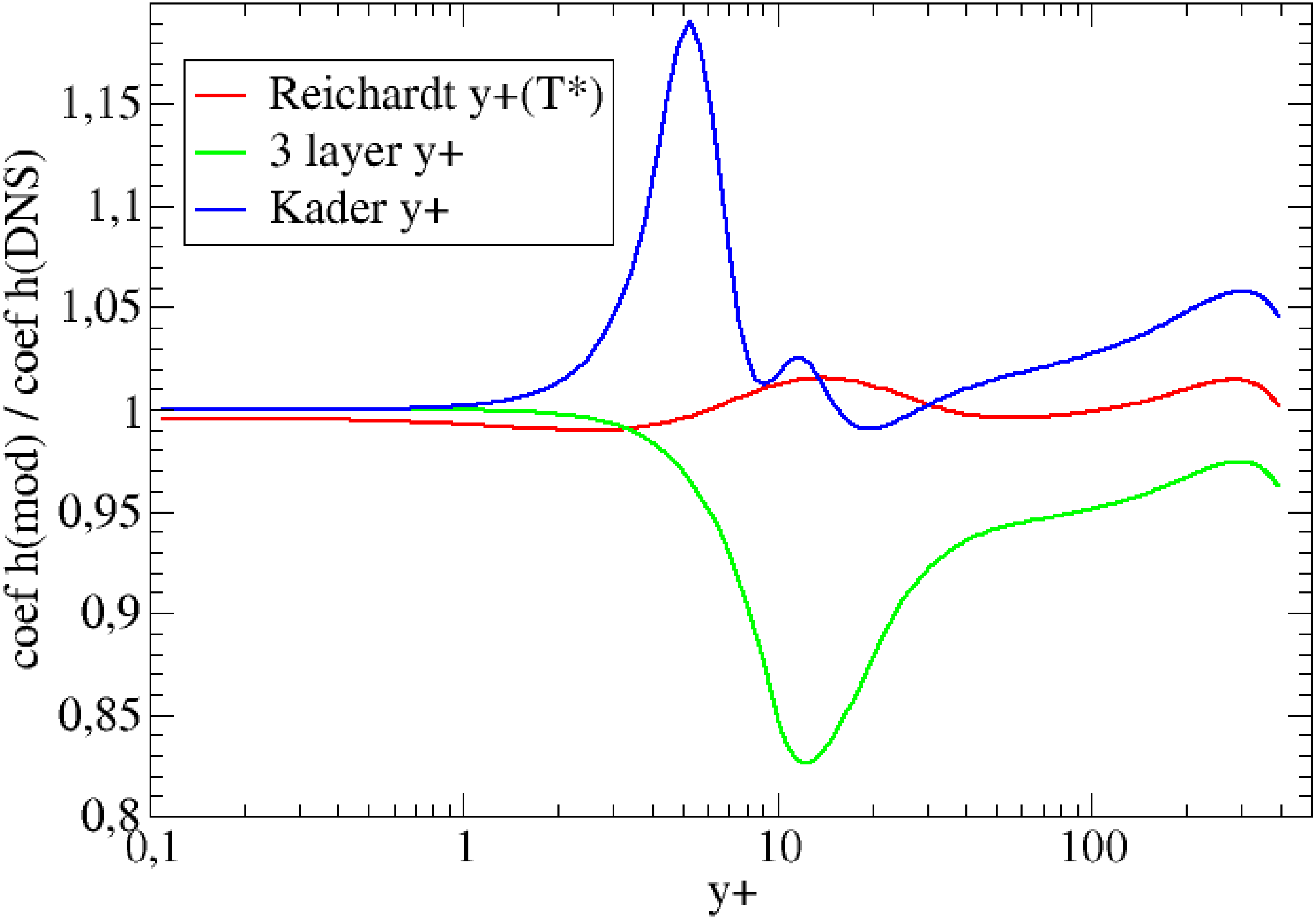
Heated channel flow: DNS vs empirical functions



Empirical functions at Prandlt = 1



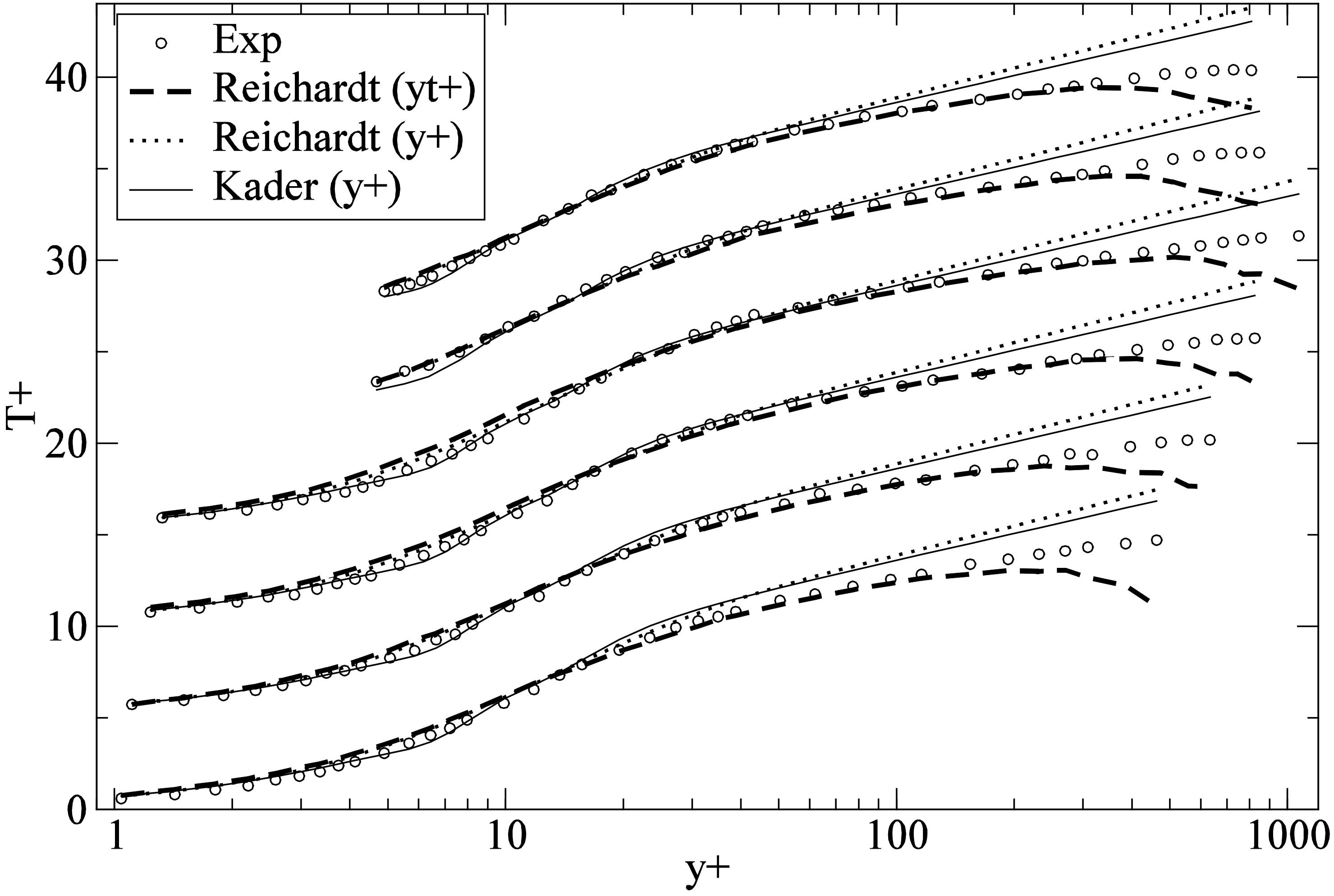
Empirical functions at : Prandlt = 1



Empirical functions and natural convection

ERCOFTAC test case :

Tsuji,1998 heated vertical flat plate experiment



Conclusions

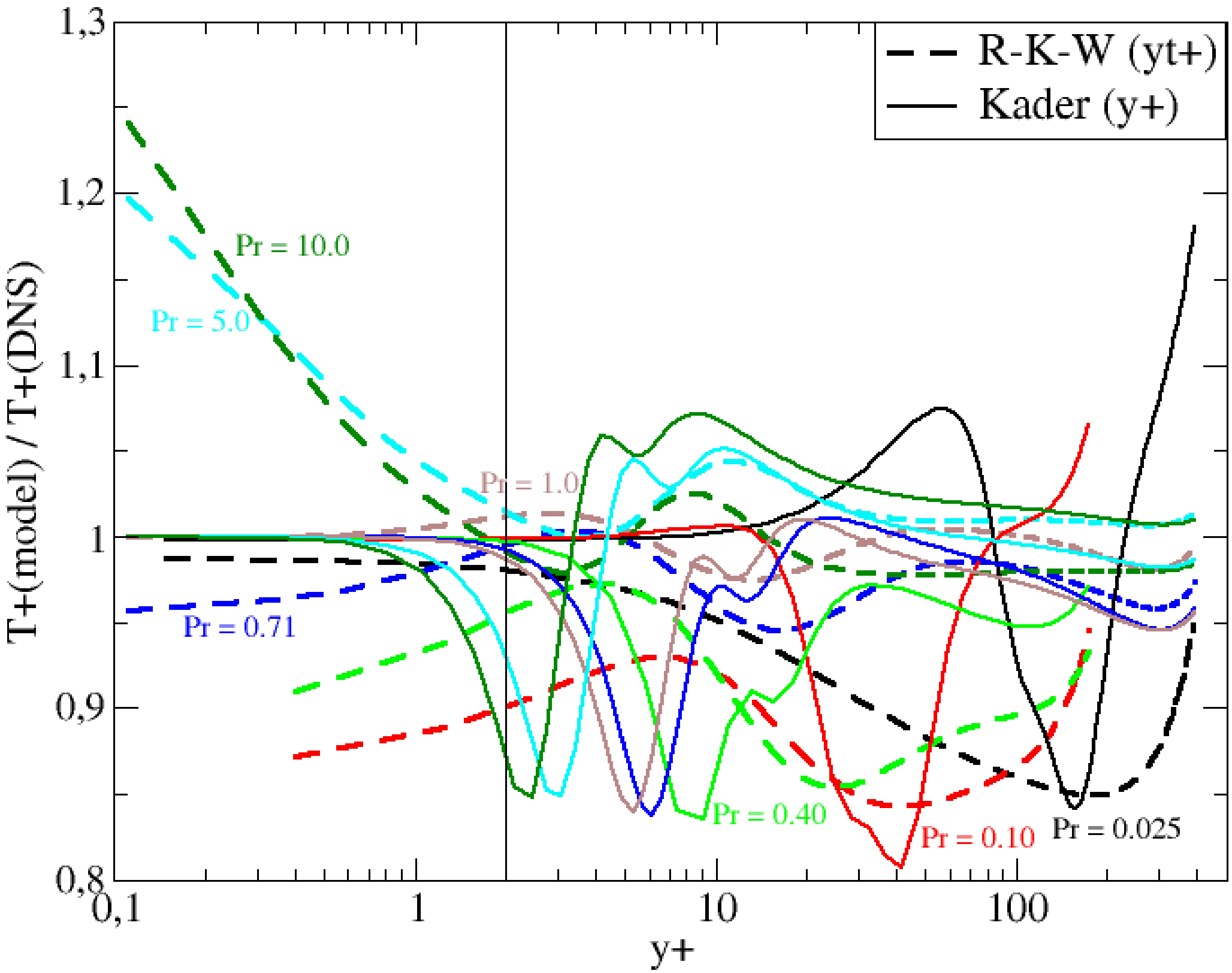
When tested on the heated vertical flat plat experiment of Tsuji and Nagano, 1988 (an ERCOFTAC test case) the new function is shown to capture the change in the log slope.

The profiles based on T+=f(y+) cannot capture.

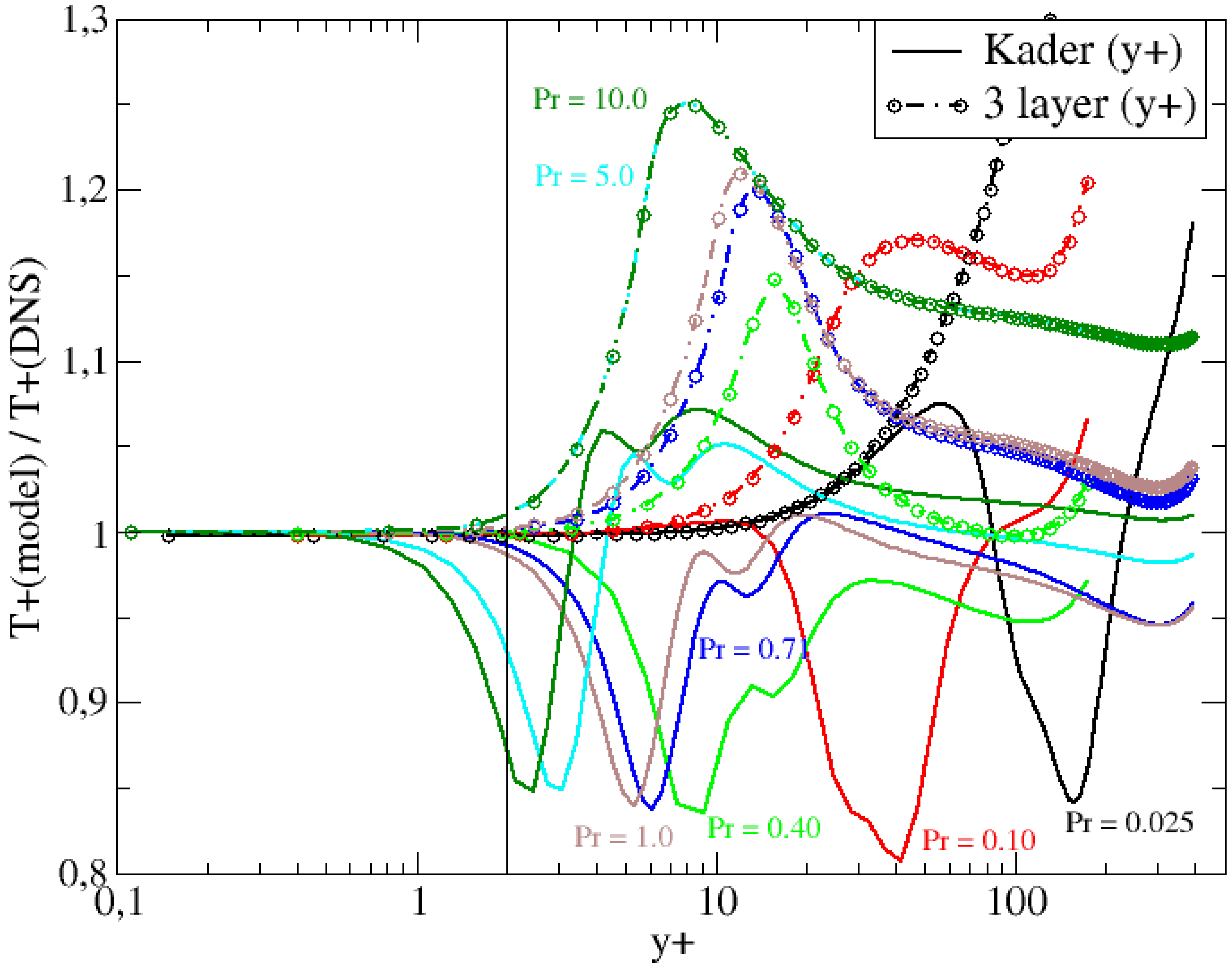
-> this suggests that the $y_T{}^{+} = y^{+}\dfrac{u^{+}}{T^{+}}$ dependence is needed to take into account natural convection effects

The function is better calibrated to the available DNS data

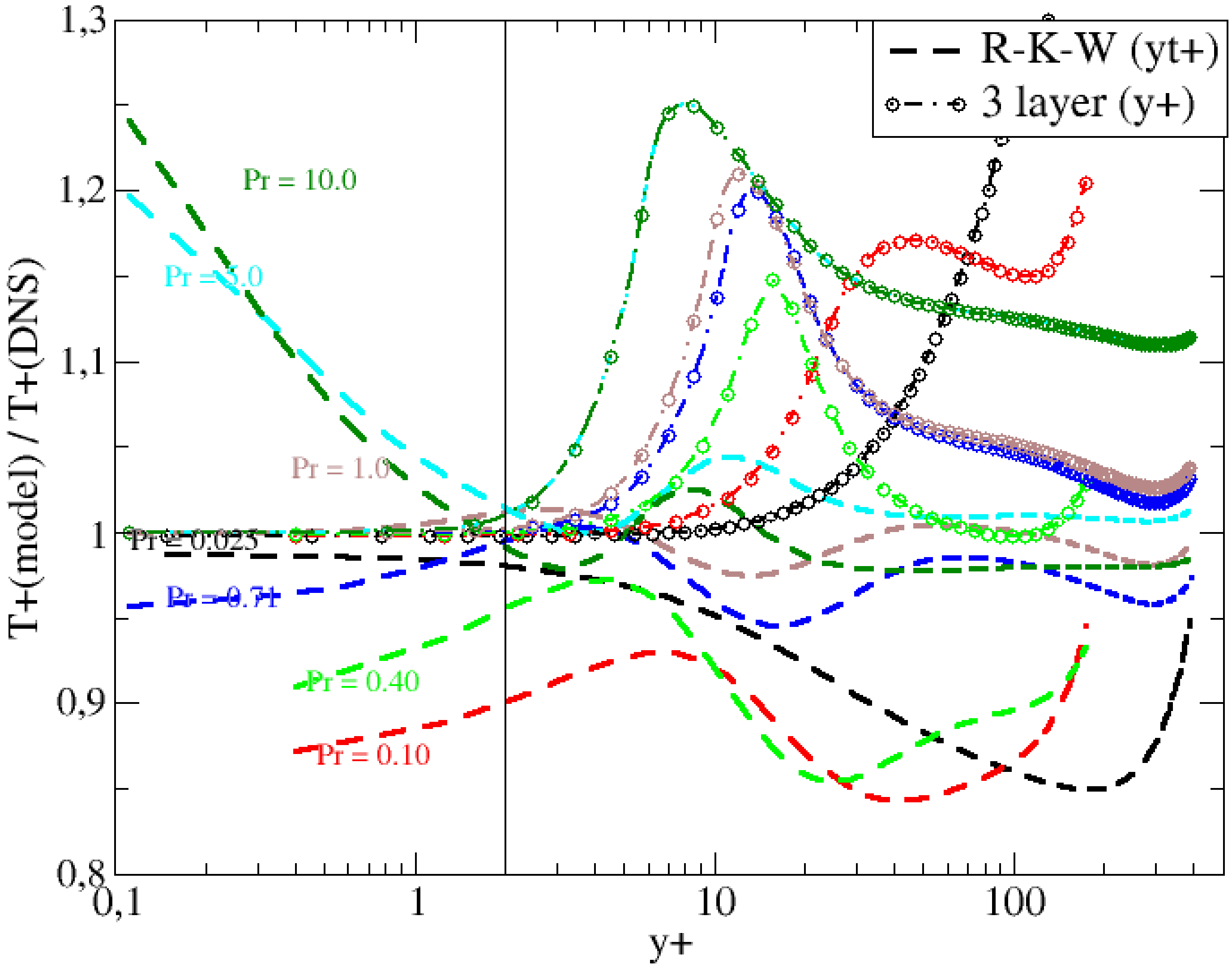
Empirical functions at different Prandtl numbers



Empirical functions at different Prandtl numbers



Empirical functions at different Prandtl numbers



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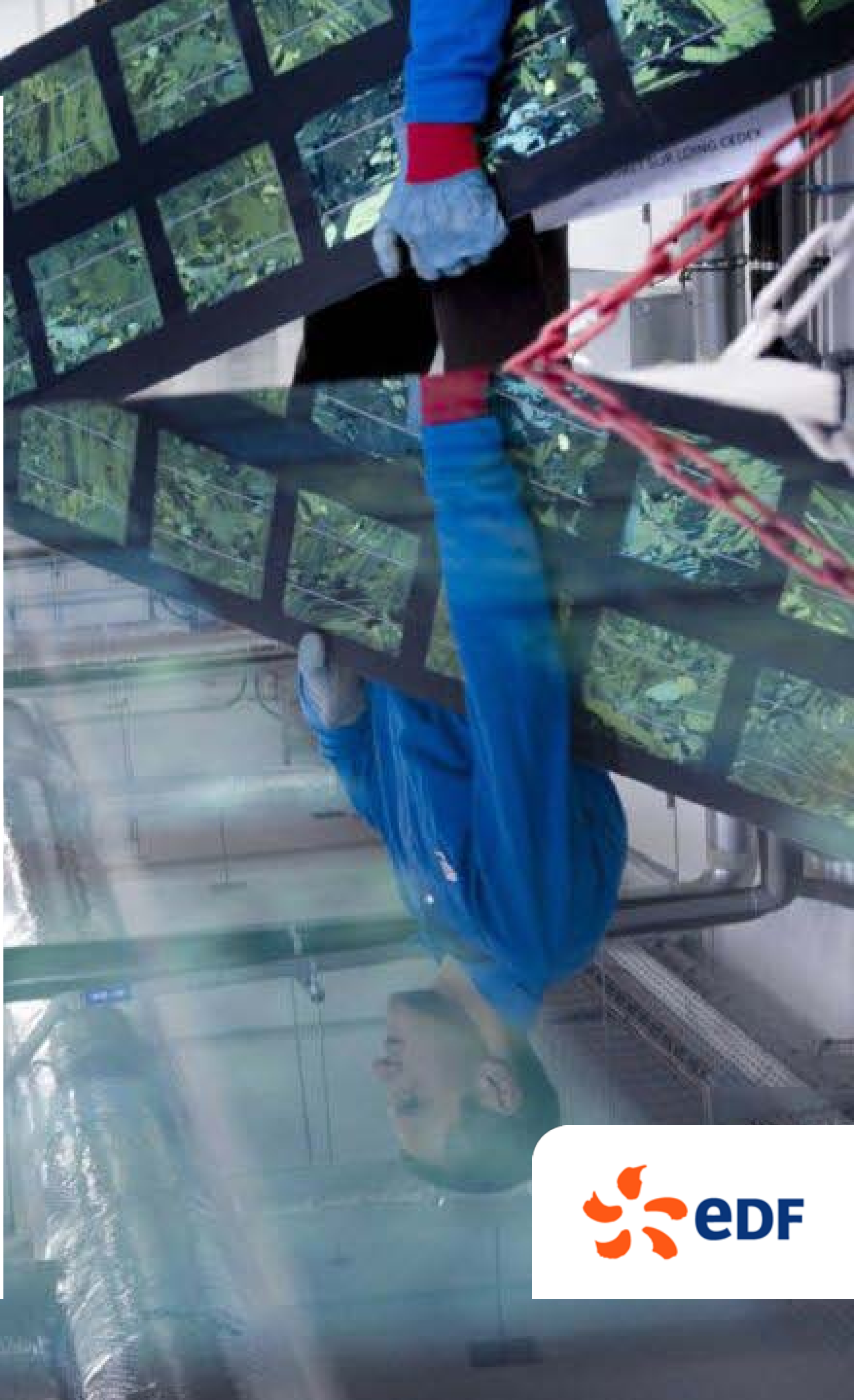


Background: Heat flux in Tee junctions

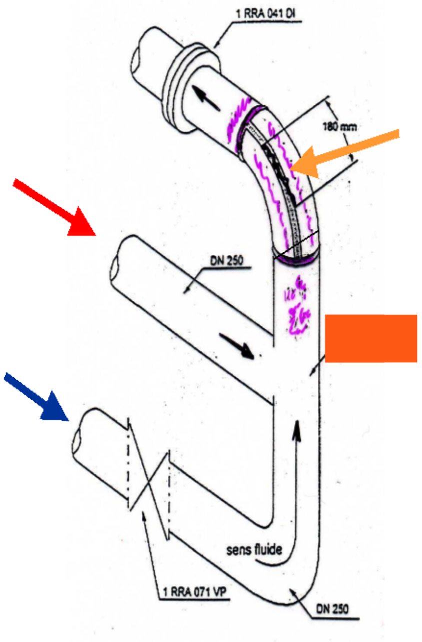
Civaux 1 EDF Pressurised Water Reactor

- leakage incident, 1998

Hot fluid injection: ~180°C

Hot inlet

Cold inlet



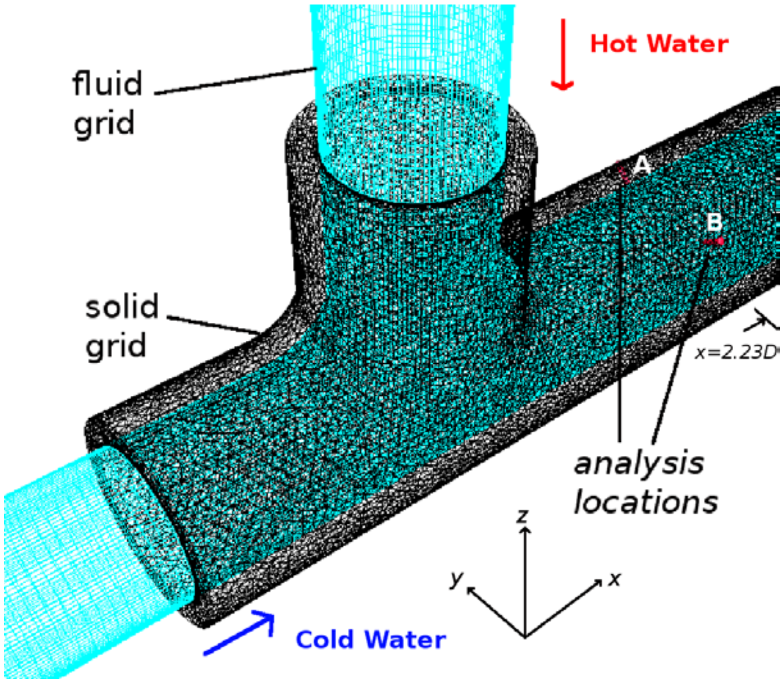
Through wall crack location

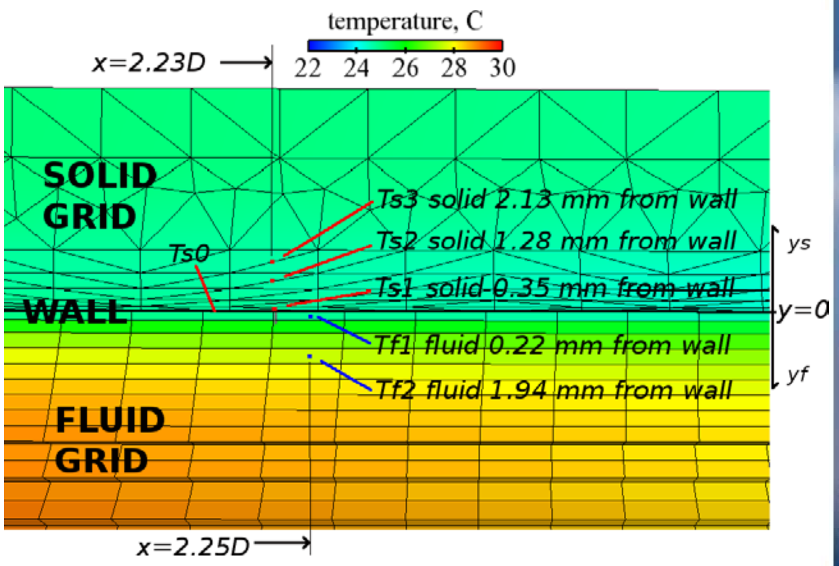
- When the reactor is stopped, a cooling circuit is opened in order to reduce the residual heat at the core
- Leaks occurred in the vicinity of the junction of the cold injection
- The leaks were due to high cycle thermal fatigue which was caused by turbulent mixing over a long period of time (several weeks)

Background: Heat flux in Tee junctions

- The CIVAUX 1 incident demonstrated that turbulent mixing combined with large temperature differences (e.g. 160°C) can cause thermal fatigue damage to the steel structure when applied over several weeks
- It is therefore important to be able to predict the heat flux between the water and the steel structure
- The friction velocity is the key parameter to evaluate the heat transfer coefficient (and hence the heat flux)
  - It is difficult to measure the friction velocity in both experiments and reactors
  - However it is much easier to measure the fluid and solid temperatures
- Moriya *et al* 2003 proposed a method to evaluate the heat flux using only fluid and solid temperature values.
- Here we use coupled solid/fluid CFD simulations to compare the heat flux obtained using the simulation temperature values applied to the method proposed by Moriya *et al* 2003 with the heat flux calculated directly using the simulation values for the friction velocity
- The T junction geometry and flow is based on the MOTHER NULIFE project

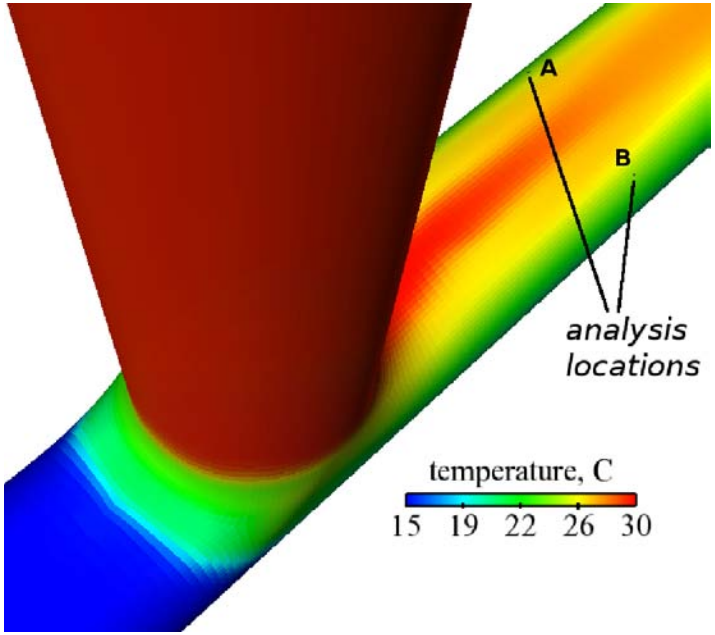
An inverse method to estimate the heat flux: an LES test

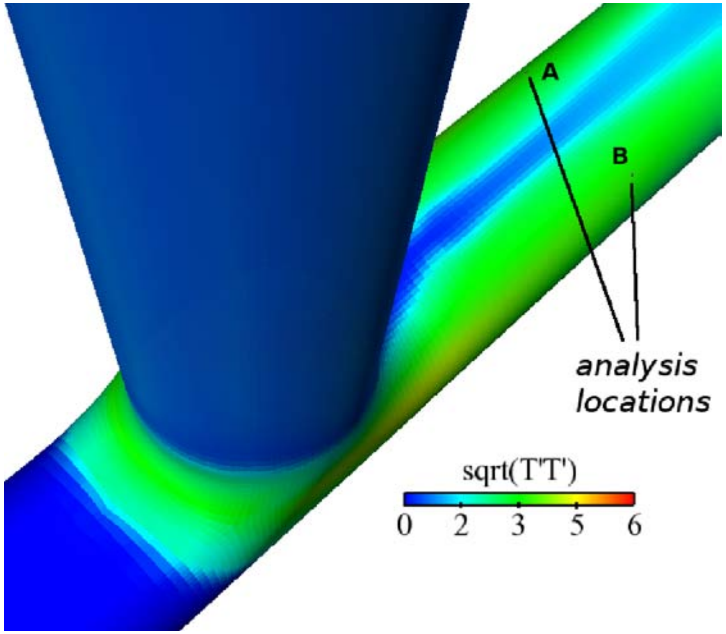




- **Fluid grid 1 000 000 hexahedra, solid grid 120 000 tetrahedra, 224.5 s**
- **Fluid - Code_Saturne, Solid – Syrthes**
- **The CFD can be used to evaluate how well the Moriya *et al* 2003 method can reproduce the CFD heat flux**

The MOTHER NULIFE project: flow set-up

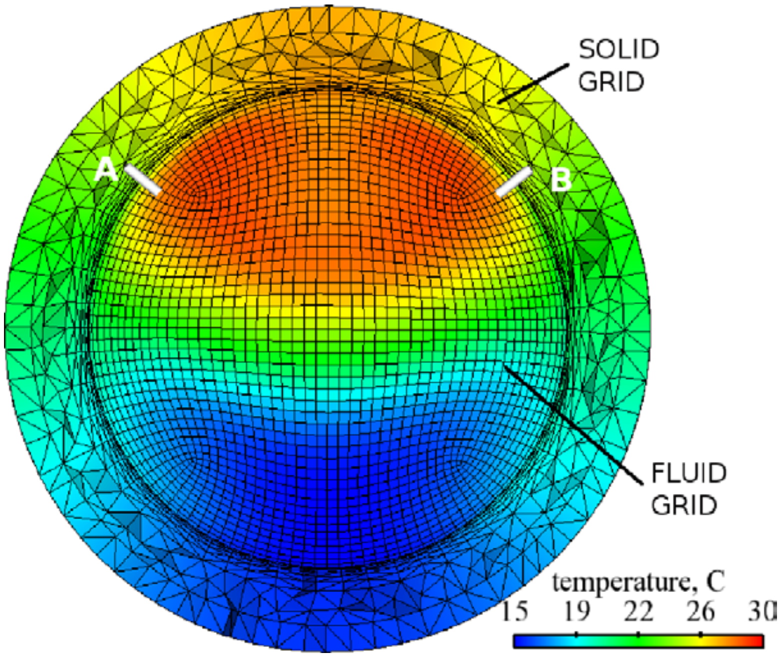


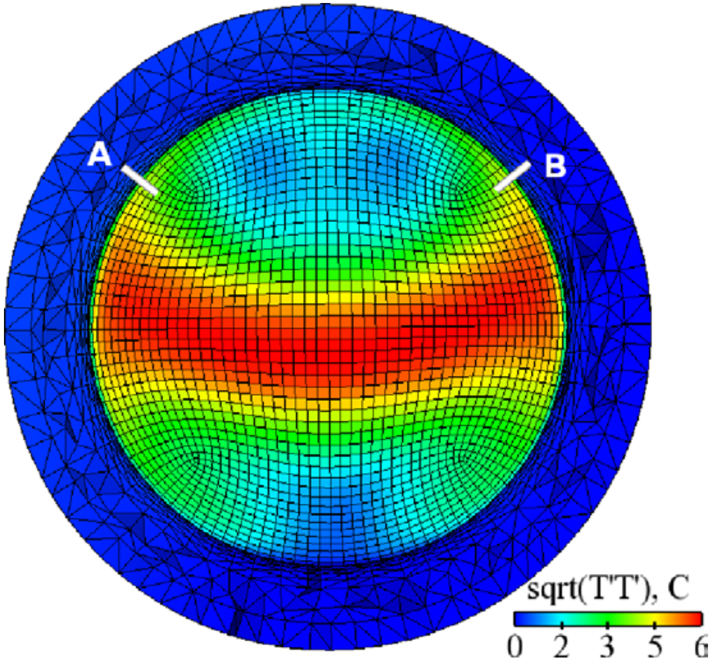


- **Hot branch water at 30°C, Cold branch water at 15°C**
- **Inlet bulk velocities of 0.35 *m/s* at each branch**
- **The downstream Reynolds number is 40 000**

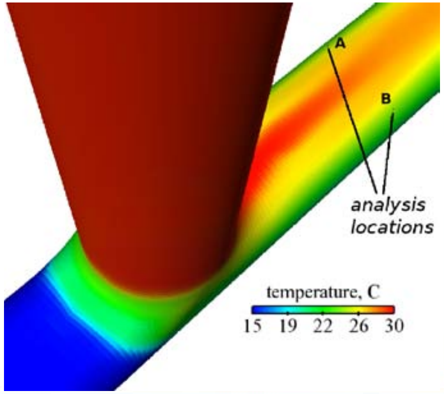
An inverse method to estimate the heat flux: an LES test

CFD to evaluate heat flux: Analysis locations





- **At 2.23D downstream of the Tee junction (0.1204 *m*)**
- **The steel is 0.01 *m* thick the fluid pipe diameter is 0.054 *m***
- **Analysis locations at +/-40° either side of the vertical axis**

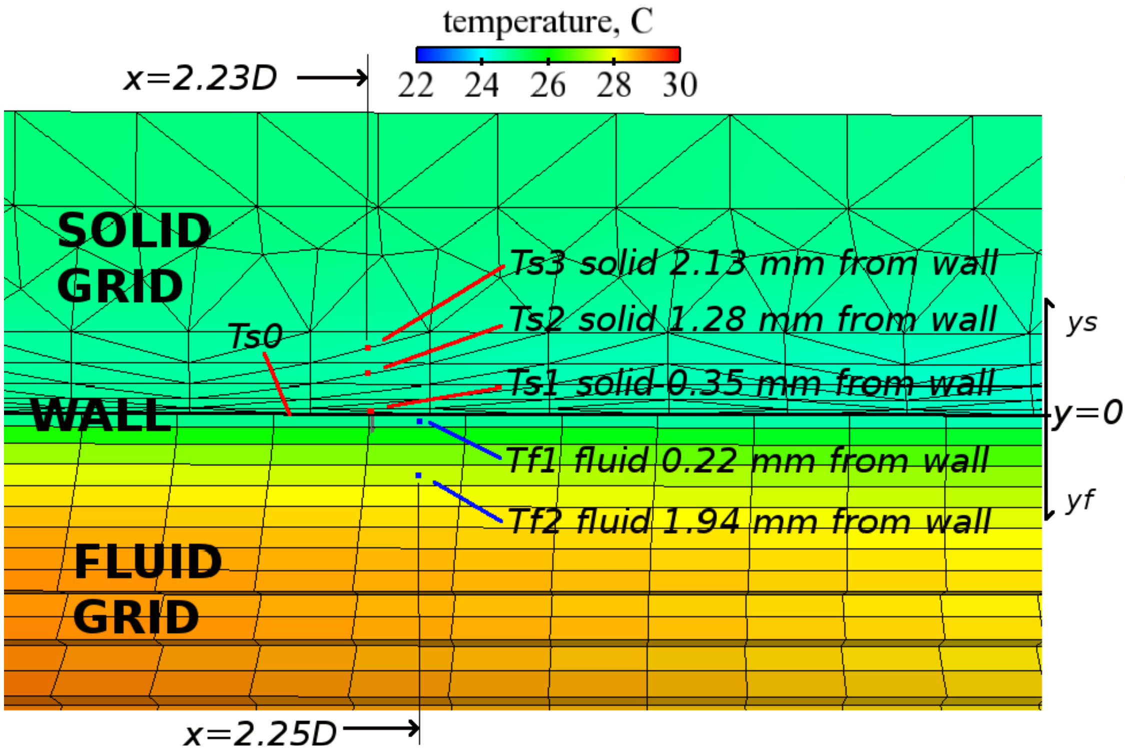


An inverse method to estimate the heat flux: an LES test

Thermal flux u_* at the wall using the friction velocity from the CFD

$$\varphi = \rho c_p u_* T^* \qquad \varphi = \underline{h(y^+)}\,\underline{\Delta T(y^+)} \qquad \underline{\Delta T(y^+)} = T_{f1}(y^+) - T_{s0}(0)$$

$$\underline{h(y^+)} = \frac{\rho c_p u_*}{T^+(y^+)}$$



- **The heat transfer coefficient is normally obtained from a relation such as the 3-layer correlation of Arpaci & Larsen, 1984 or the Kader, 1981 correlation**

Coarse LES used in a method to estimate the heat flux

Thermal flux FT$\langle\varphi\rangle$ using only temperature values

$$\langle\varphi\rangle = \underline{\tilde{h}(f)}\,\underline{\langle\Delta T(f)\rangle}$$

$$\underline{\tilde{h}(f)} = \frac{\sqrt{\pi\rho c_p\lambda f}}{\sqrt{\dfrac{\dfrac{e^{-ca}}{|G^2|}-\dfrac{1}{2}}{2}-\dfrac{1}{2}}}$$

$$\underline{\langle\Delta T(f)\rangle} = \langle(\boxed{T_{fi}(y^+)} - \boxed{T_{s0}(0)})\rangle$$

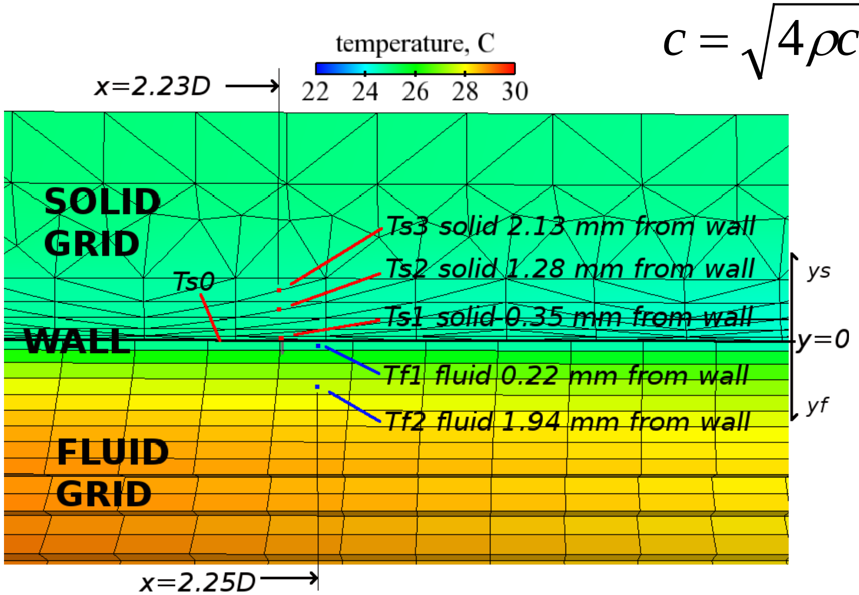
$$c = \sqrt{4\rho c_p f/\lambda}$$

- The 1D heat transfer method was obtained from **Moriya *et al* 2003**
- The frequency response function

$$|G^2| = \boxed{\frac{\psi_{sj}}{\psi_{fi}}}$$

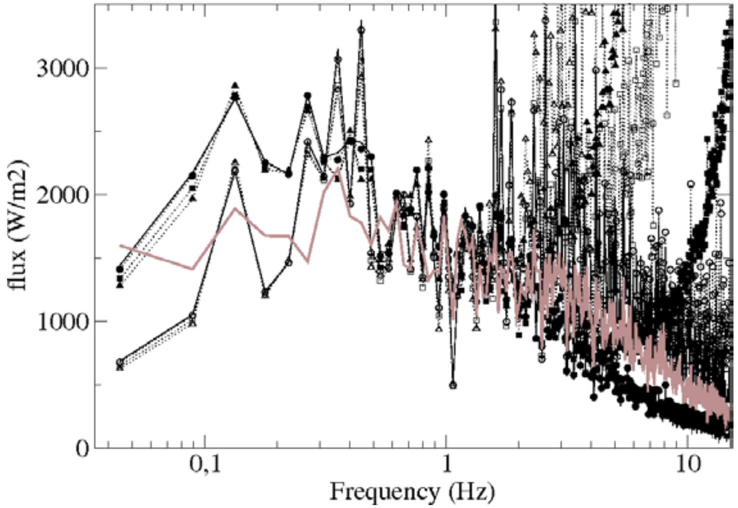
represents the ratio between the **solid and fluid temperature power spectral densities**

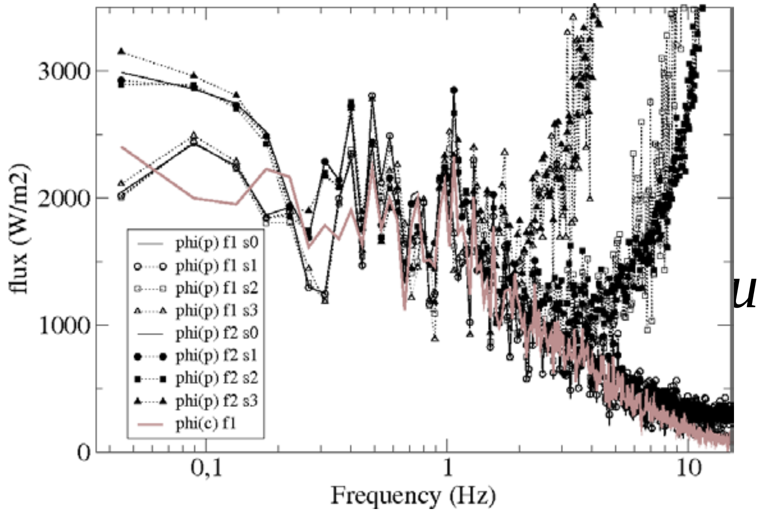
- The result is the Fourier transform of the heat flux



An inverse method to estimate the heat flux: an LES test

Comparison of the Fourier transform of the thermal flux $\langle\varphi\rangle$

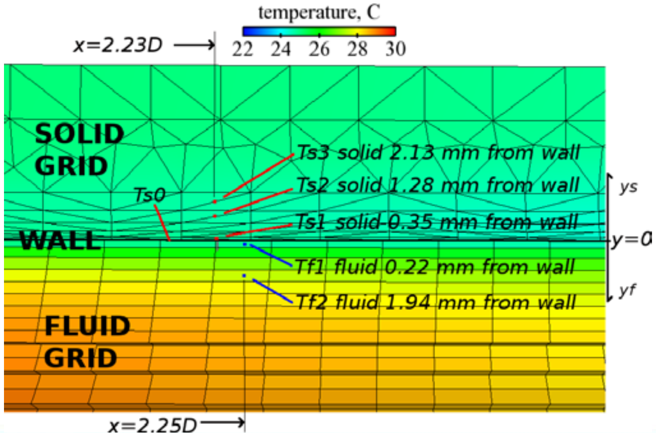


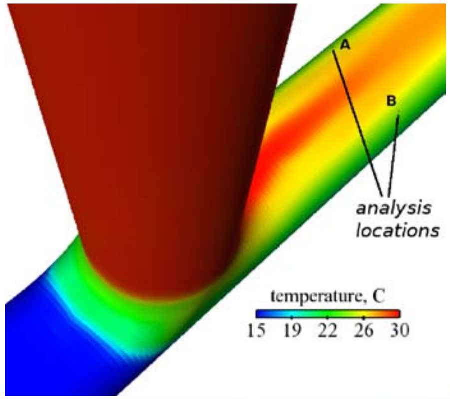


u_*

- **Analysis location A**

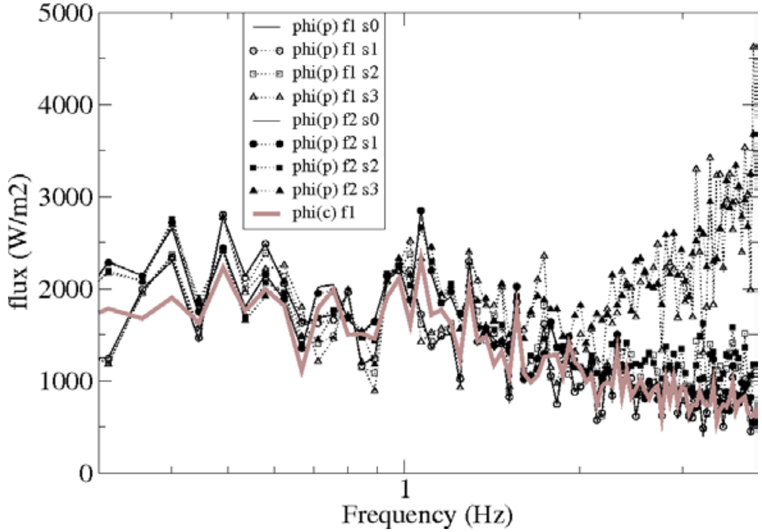
Analysis location B

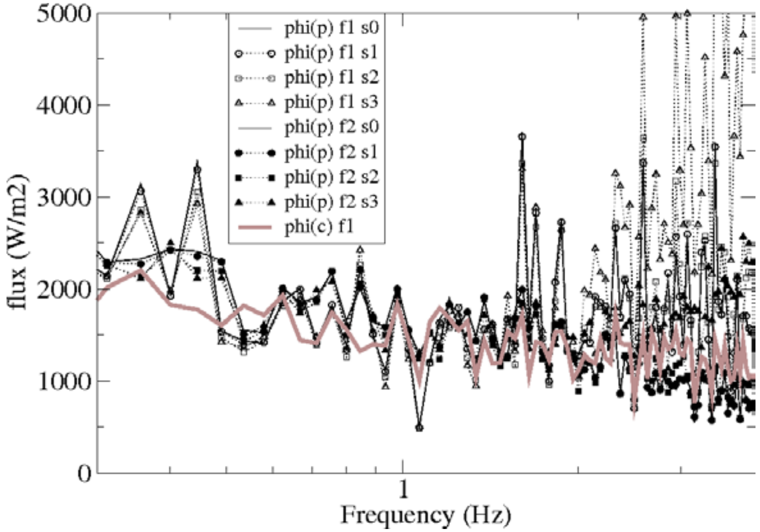




An inverse method to estimate the heat flux: an LES test

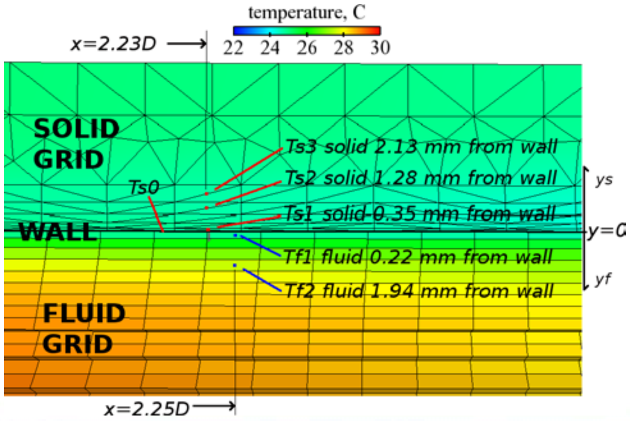
Comparison of the Fourier transform of the thermal flux $\langle \varphi \rangle$

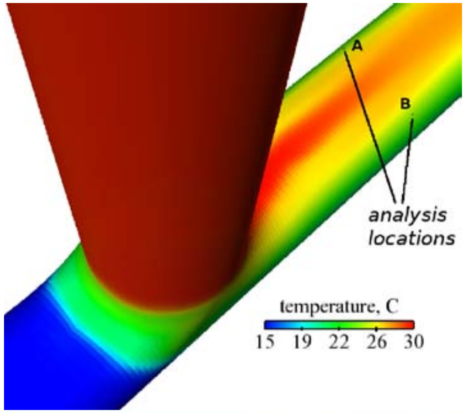




- **Analysis location A**

Analysis location B





An inverse method to estimate the heat flux: an LES test

Conclusion: thermal flux values can be predicted when we only know the temperature in the solid and the fluid

- The CFD thermal flux is quite well reproduced using the simulated temperature power spectral densities applied to the method of Moriya *et al* (2003)
  - The method is designed for steady state problems
  - The method is derived for 1D heat transfer between the fluid and the solid
- At high frequencies, the solid signal is attenuated by the depth of the thermocouple in the solid (steel)
  - at a depth of 0.35 *mm*, the highest frequency that is captured to within 15% is about 6 *Hz*
  - at 1.28 *mm* it is about 1.5 *Hz*
  - at 2.13 *mm* it is about 1 *Hz*
- Low frequencies (< 0.4 Hz) require a longer statistical sample (currently 224.5 s)

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- **LES on non-structured grids**
- A practical example of non-structured simulations in complex geometries

LES on Tetrahedral grids

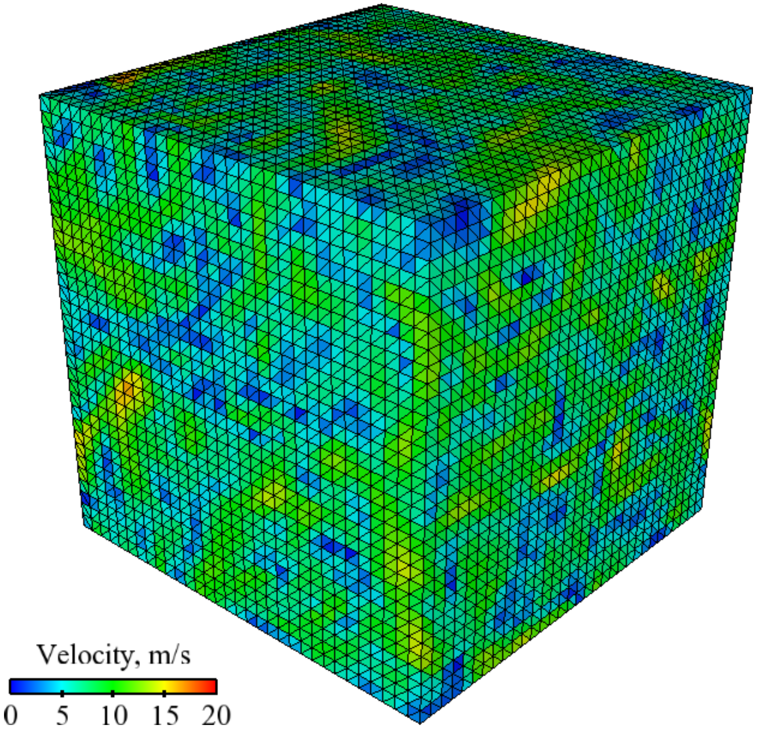
- **Numerical scheme**
- **Evaluation for homogeneous isotropic turbulence**
- **Evaluation for turbulent channel flow**
- **Conclusions**

LES on Tetrahedral grids

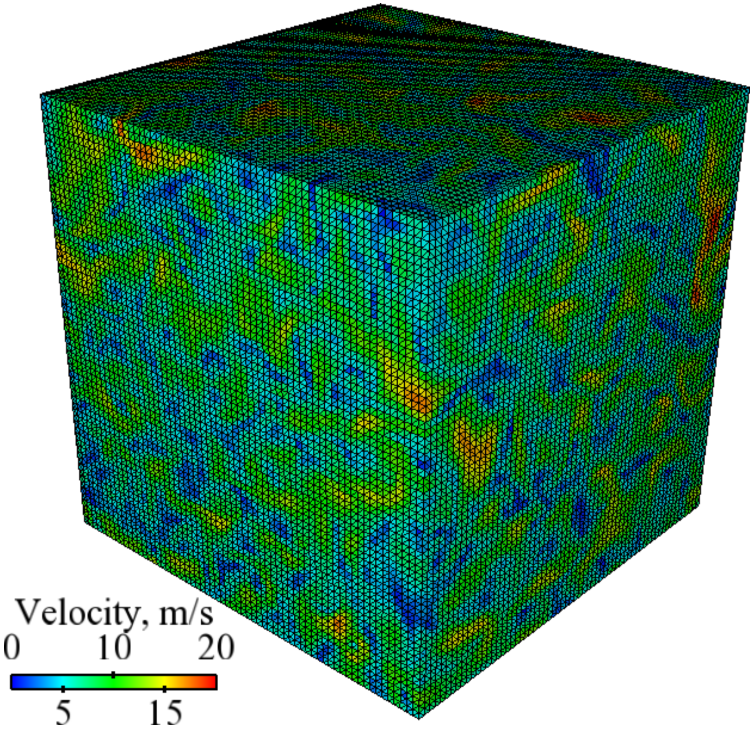
- **Simulations with Code_Saturne version 2.0**
- **Co-located cell centred Navier-Stokes solver**
- **Reconstruction of local gradients on non-orthogonal grids using a least squares fit to neighbours that share the same nodes or corners.**
- **Convection scheme: Second Order Linearised Upwind Scheme (SOLU) of Warming and Beam, 1976**
- **Time scheme: Crank-Nicolson**

LES on Tetrahedral grids

Homogeneous Isotropic Turbulence



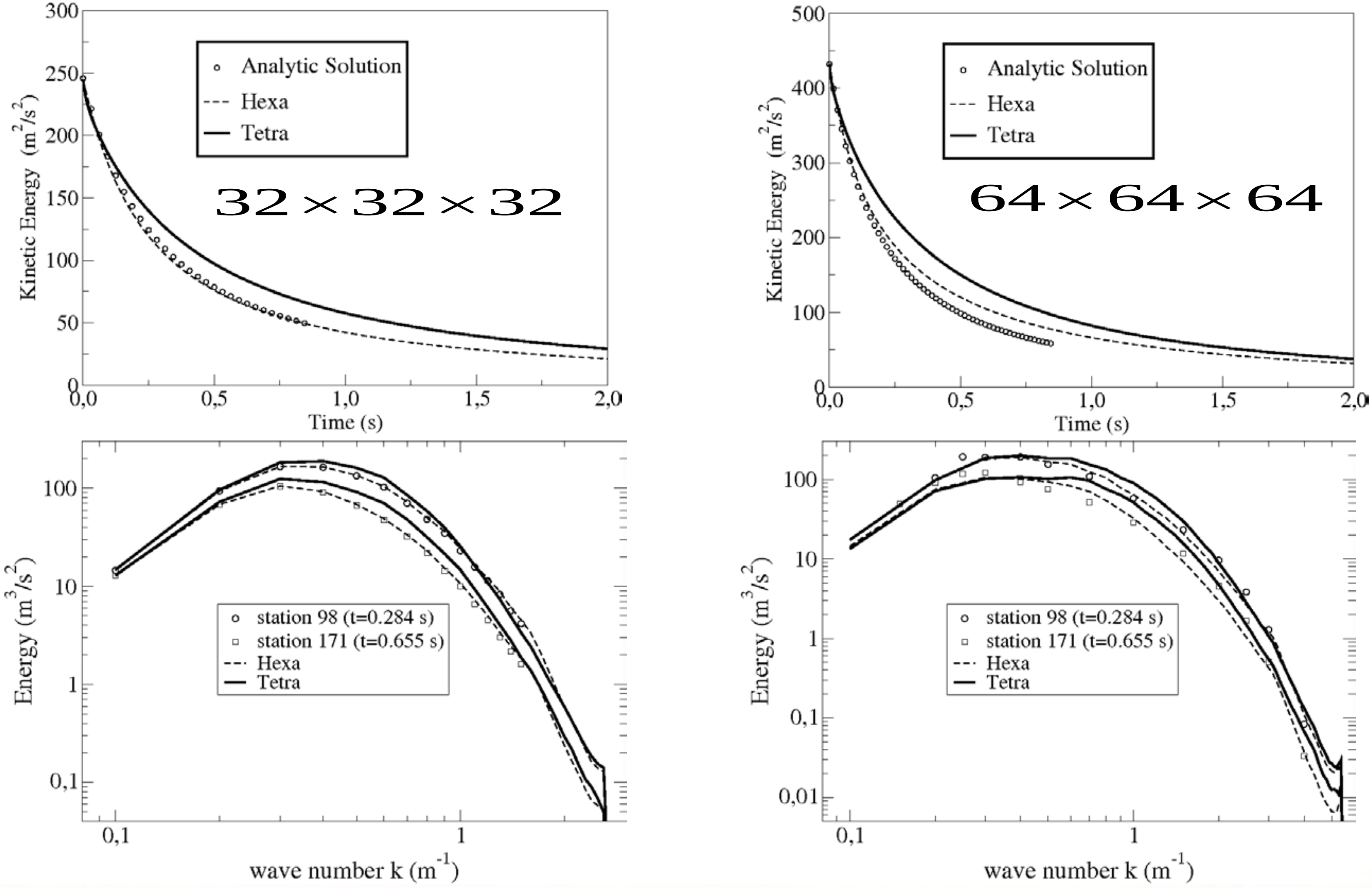
$32 \times 32 \times 32$



$64 \times 64 \times 64$

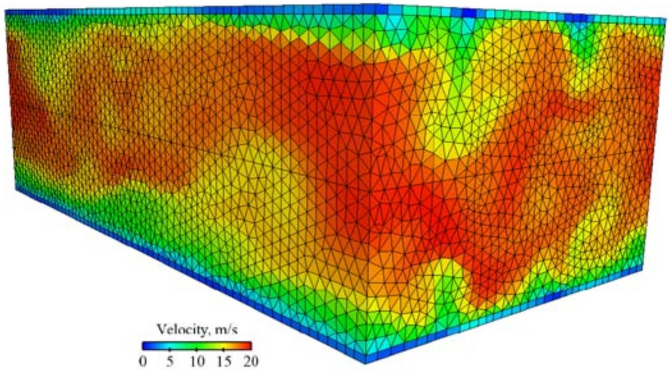
LES on Tetrahedral grids

Homogeneous Isotropic Turbulence

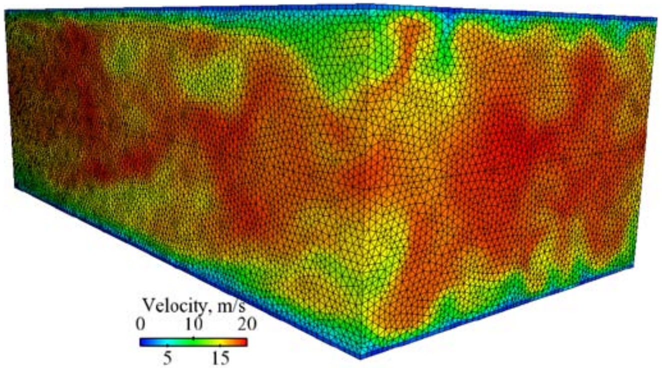


LES on Tetrahedral grids

Turbulent Channel flow, Re(u*) = 180

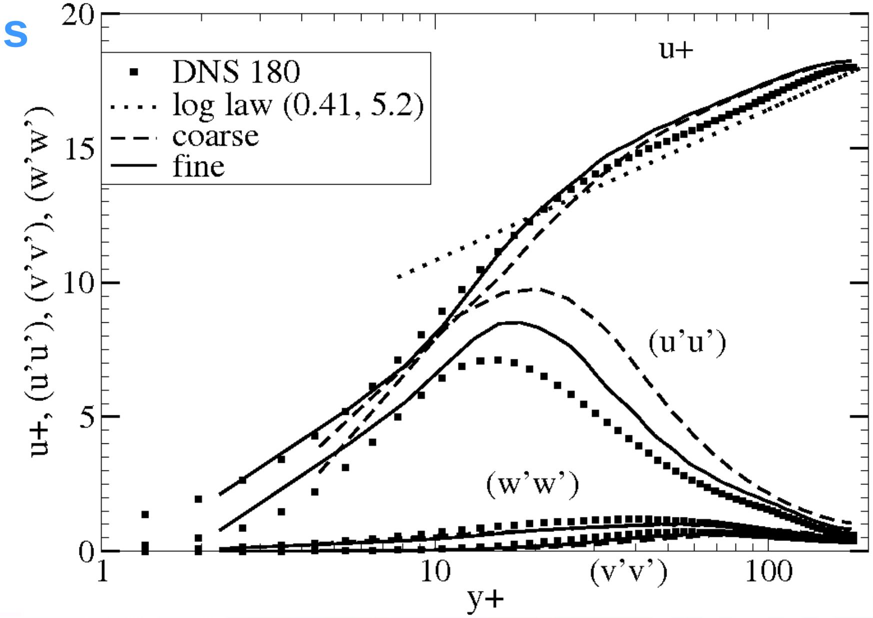


$$\Delta x^+ = \Delta y^+ = \Delta z^+ = 18$$



$$\Delta x^+ = \Delta y^+ = \Delta z^+ = 9$$

500 000 cells



4 million cells

LES on Tetrahedral grids

Conclusions

- The numerical scheme is stable and does not damp out local turbulent structures.
- Although the coarse channel flow simulation shows that some local flow structures are damped.
- The fine channel flow simulation reduces this effect.

ETMM9 Thessaloniki | Greece

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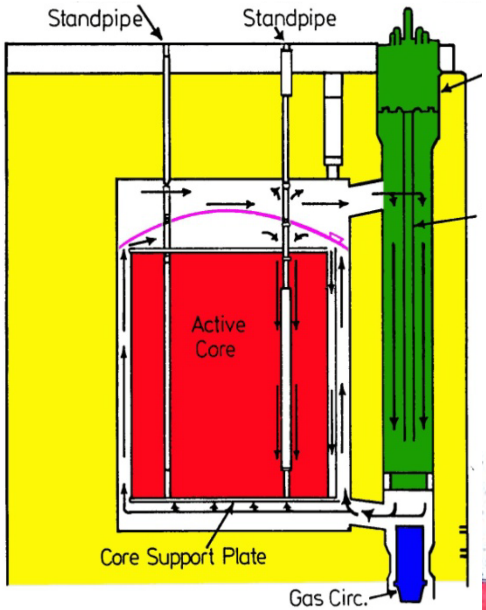
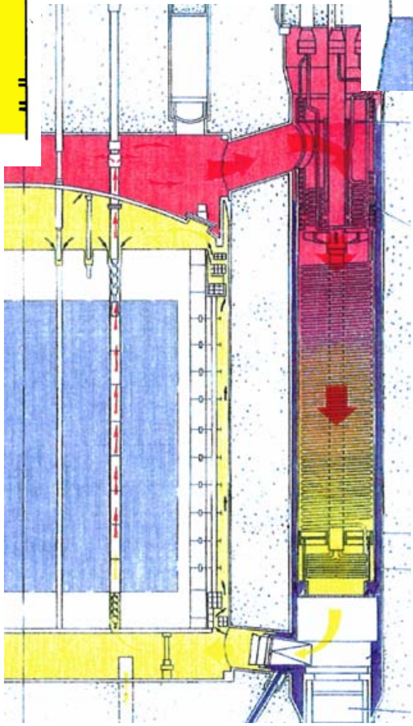
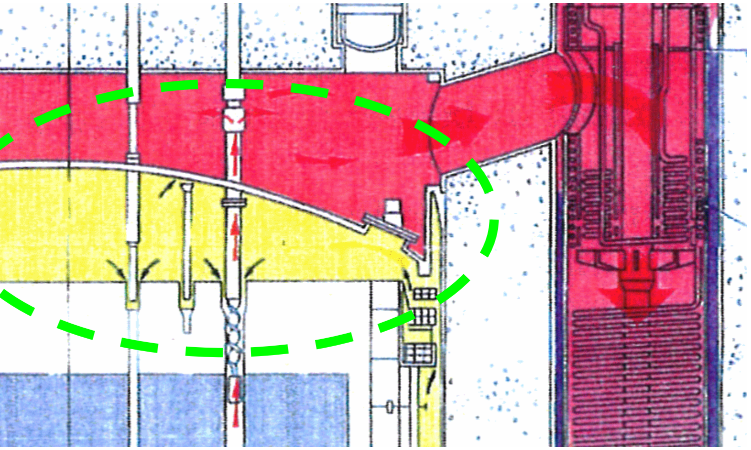
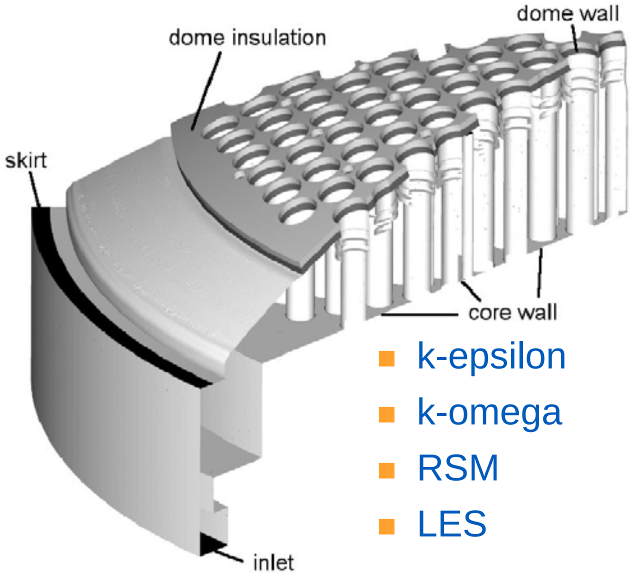
AGR Reactor - Hot Box Dome heating





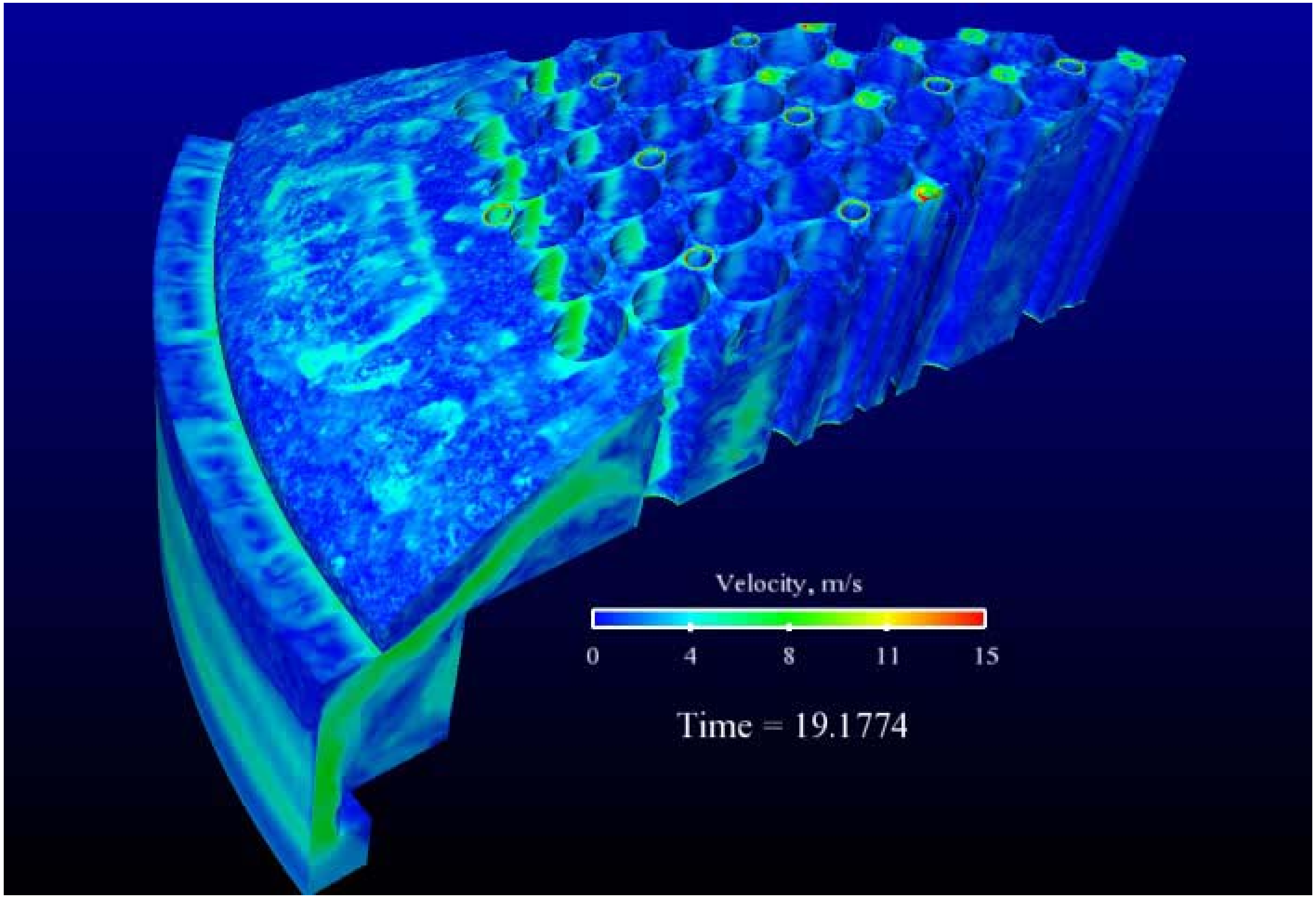


- 1/8th model
- Fluid 13M tetras
- coupled solid/fluid

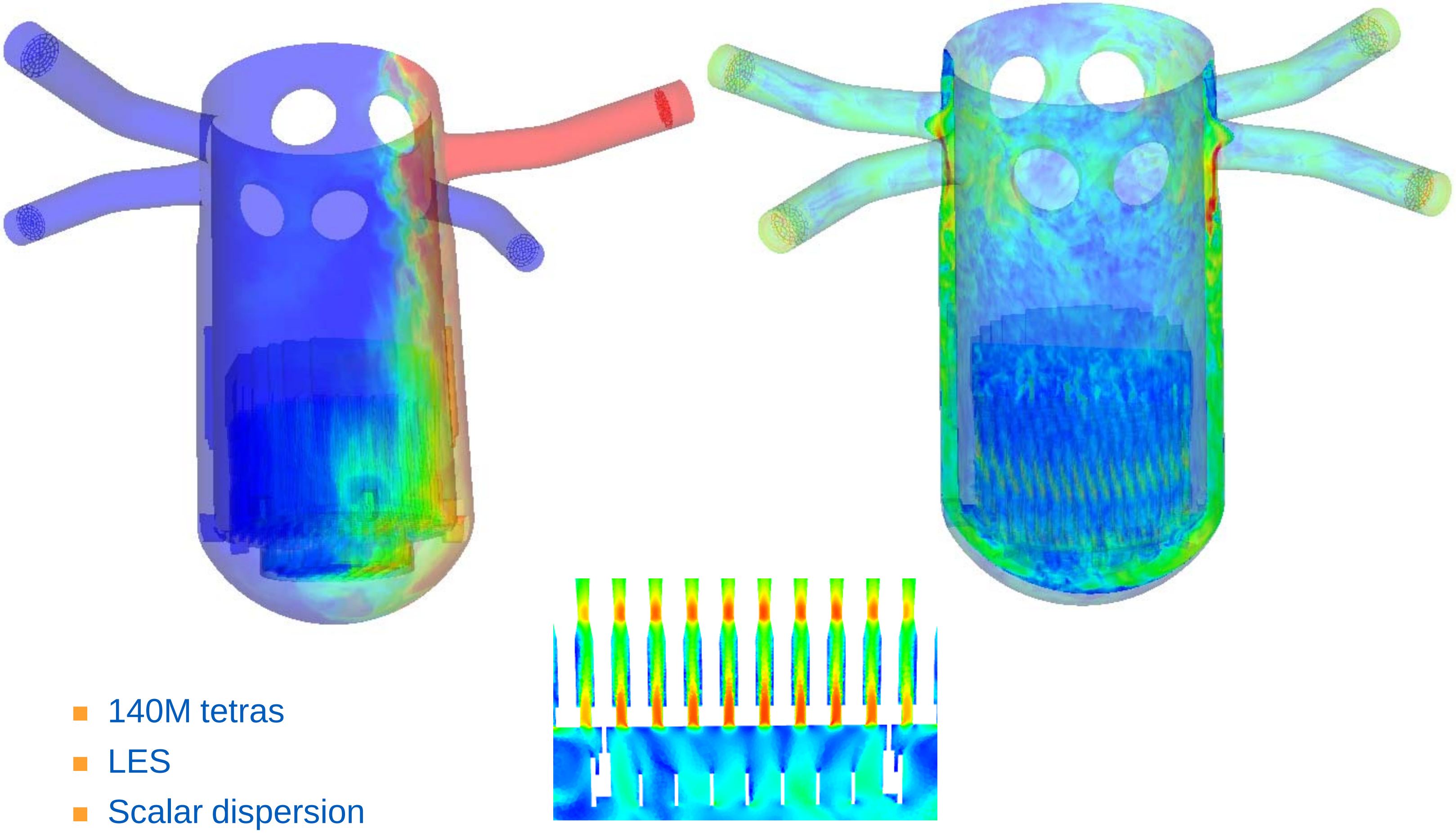


- k-epsilon
- k-omega
- RSM
- LES

AGR Reactor - Hot Box Dome heating

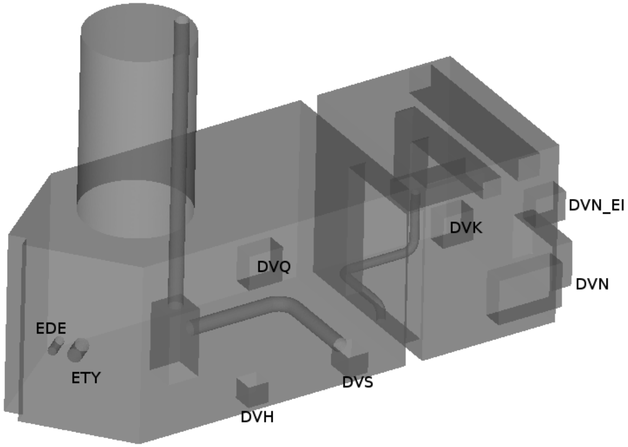


EPR Reactor – Core inlet flow



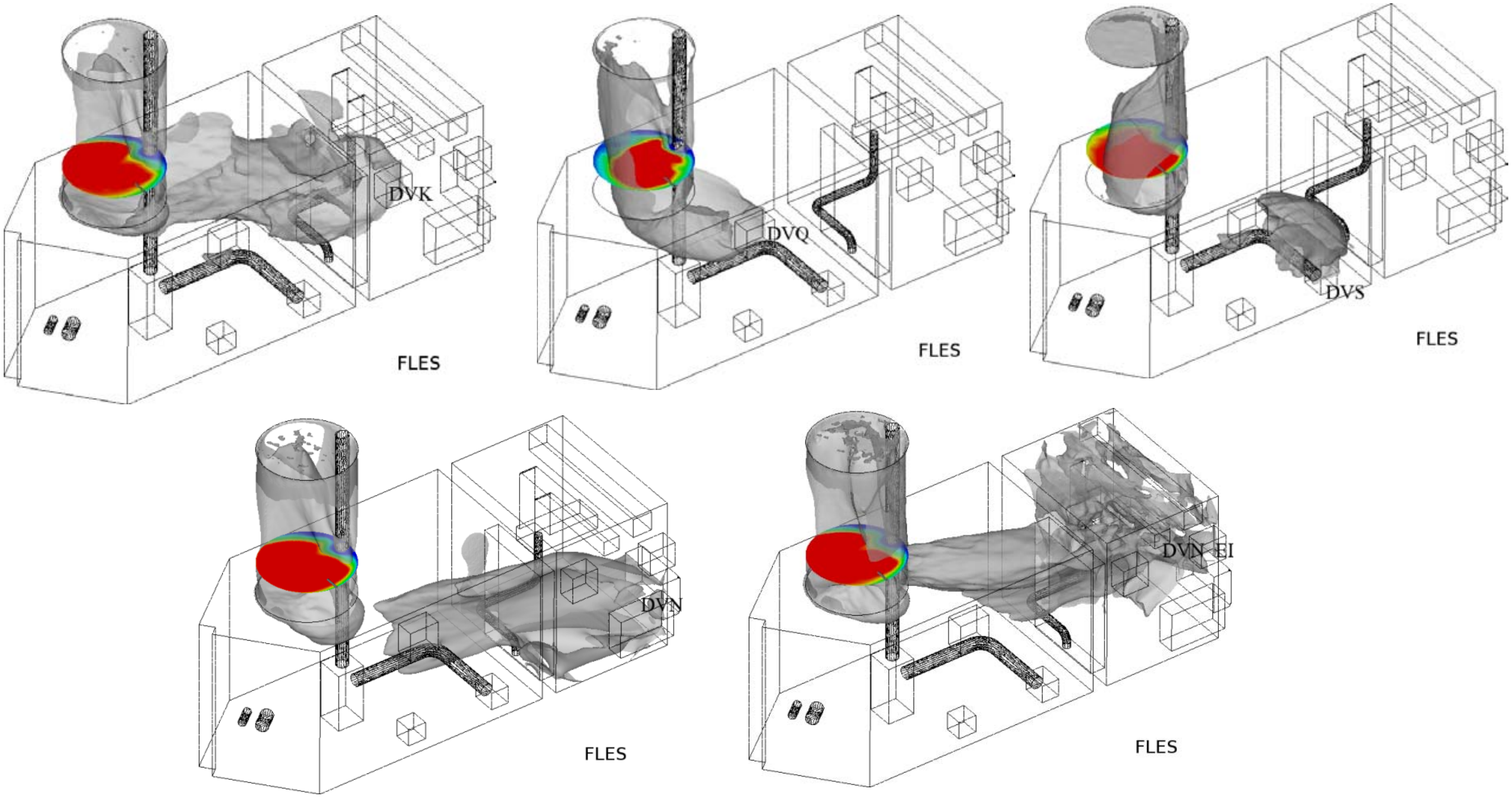
- 140M tetras
- LES
- Scalar dispersion

PWR Reactor – Auxiliary Building ventilation



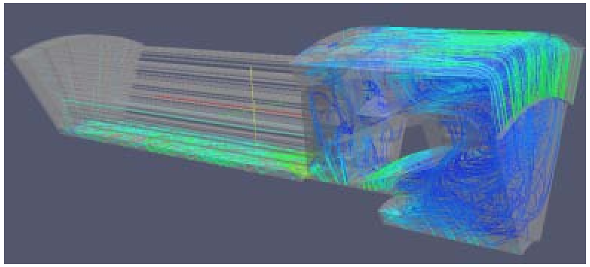
- Scalar dispersion
- up to 11M tetras
- Several turbulence models
  - k-epsilon
  - k-epsilon linear production
  - k-omega
  - RSM
  - LES

PWR Reactor – Auxiliary Building ventilation



- 2 grids (1.2M and 10.7M tetras)
- 5 turbulence models
- 5 scalars

Studies using the same type of approach



- Looking for hotspots in Alternators
- Gilles Roland (THEMIS)

- Studying vibration in the Steam Generator
- Anatole Weill and Julien Berland (I84)