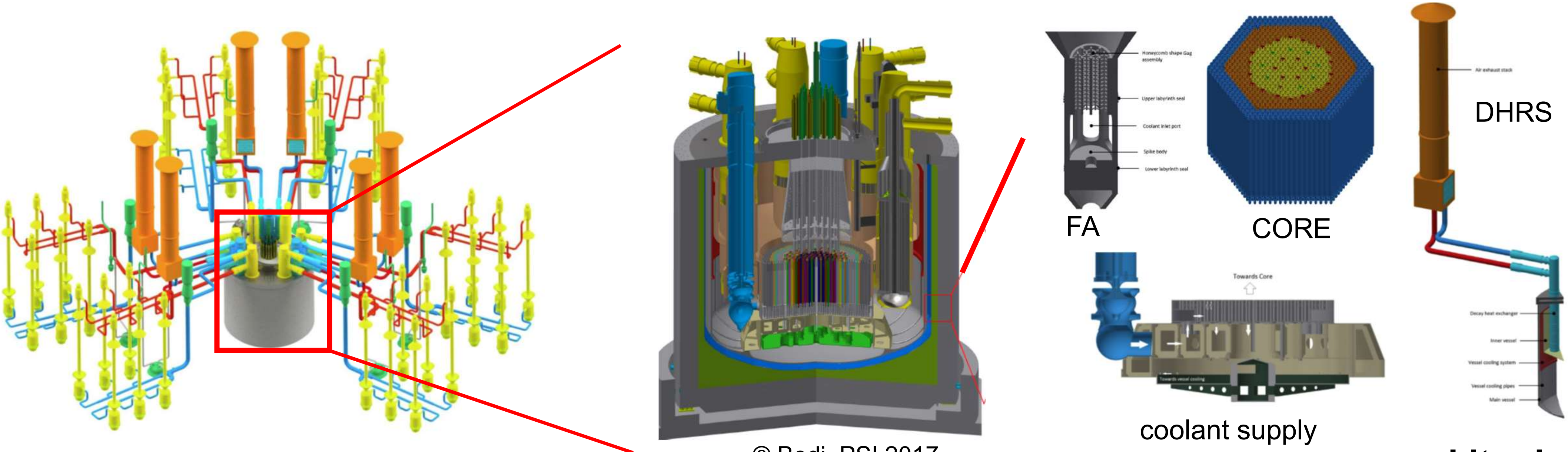
Karlsruhe Institute of Technology

ESFR-SMART
sodium fast reactor safety

SFR Thermalhydraulics

Robert Stieglitz

(input taken from current ESFR-SMART, SESAME, THINS, CP-ESFR,…; ASCHLIM – 2 decades of EUROPEAN Support) not to mention various projects in support to Pb, LBE reactor development)



© Bodi, PSI,2017

CONTENT - OUTLINE

- SFR – LWR (PWR)*
  - Features SFR vs. PWR
  - Fundamental equations & dimensionless quantities
  - thermo- physical quantities & their impact in reactor applications quantities
- Thermal-hydraulics in reactor applications
  - Challenging flow domains of SFR
  - Flow modelling - General ideas, hierarchy and approaches (DNS, LES, System-Thermalhydraulics-STH)
  - Some applications
    - Core (forced, mixed convection ?)
    - Pool (jets –flow separation, buoyancy – uppper plenum)
- Synopsis

* single-phase problem

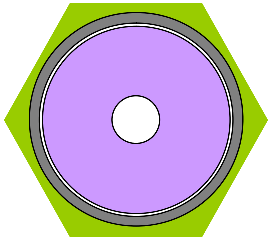
SFR-LWR (design features)

SFR NEUTRONIC FEATURES

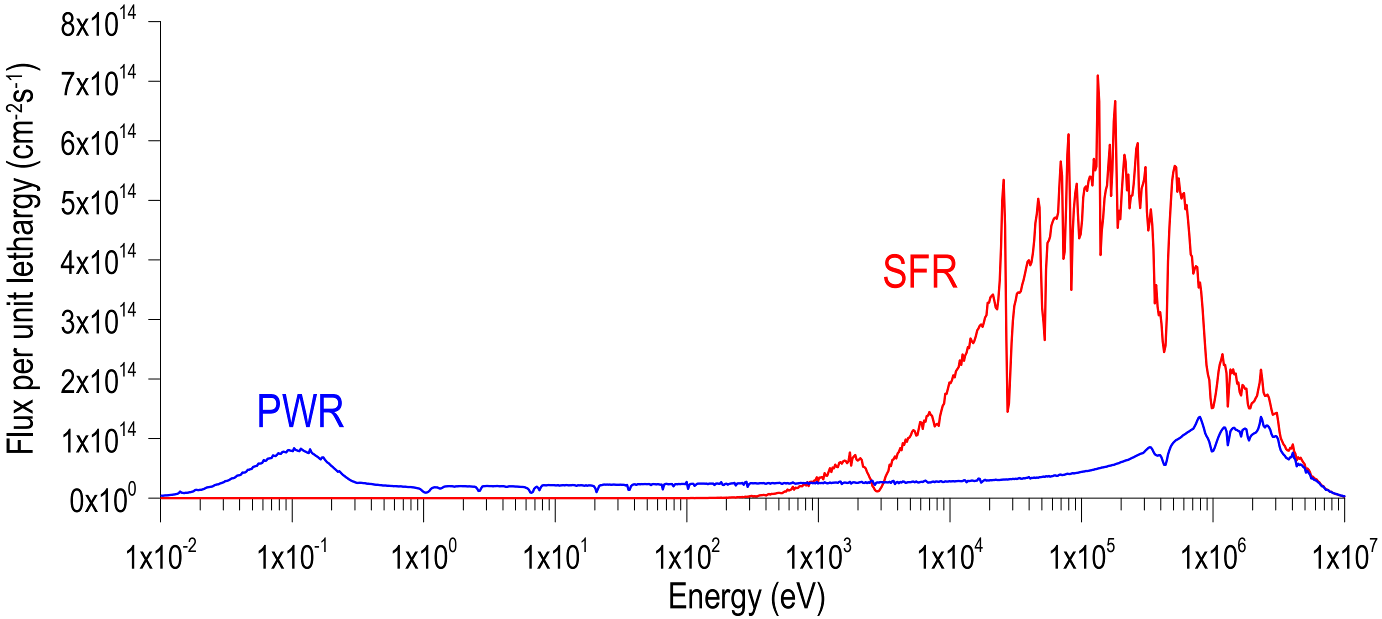
- fission chain reaction sustained by fast neutrons, $\overline{E_n} \sim 10keV$
- no need for neutron moderator (mean free path $l \sim 40cm$)
- requires highly enriched fissile material (>>10%)

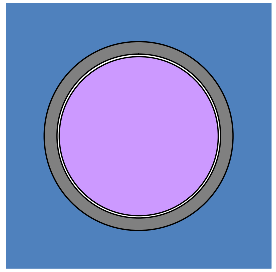
PWR NEUTRONIC FEATURES

- dominated by thermal neutrons, $\overline{E_n} \sim 25meV$
- coolant as moderator (mean free path $l \sim 1cm$)
- requires low enriched fissile material (~5%)



SFR-FA
~ 270 pins
D=7.0-8.5mm,
P/D~1.2





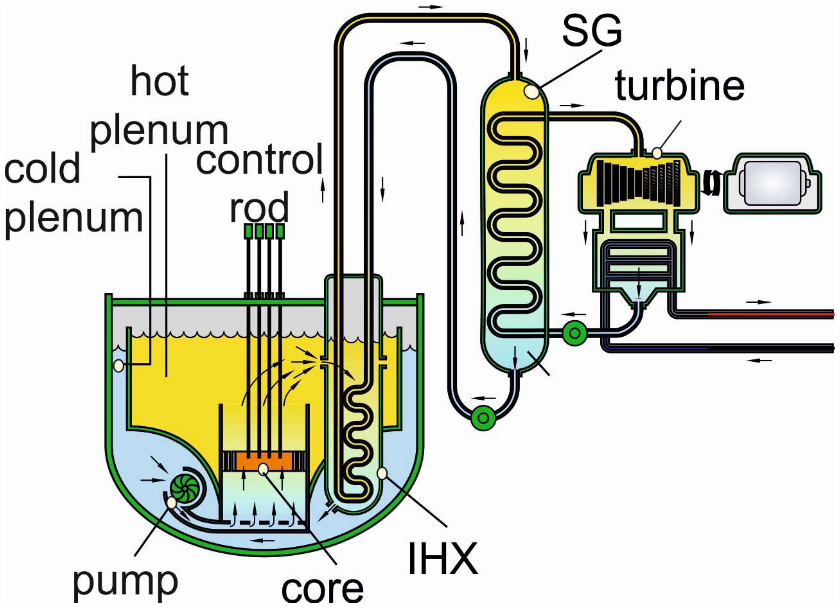
PWR-FA
~ 280 pins
D=9.5mm,
P/D~1.3-1.4

KEY FEATURES of FAST REACTORS

- **higher flux (factor 10)** ➡ **material damage (+activation+transmutation products+……)**
- **higher volumetric power** ➡ **high temperature gradients, higher core ΔT**
- **fast in all views** ➡ **(neutronics -many groups, TH- TM transients)**

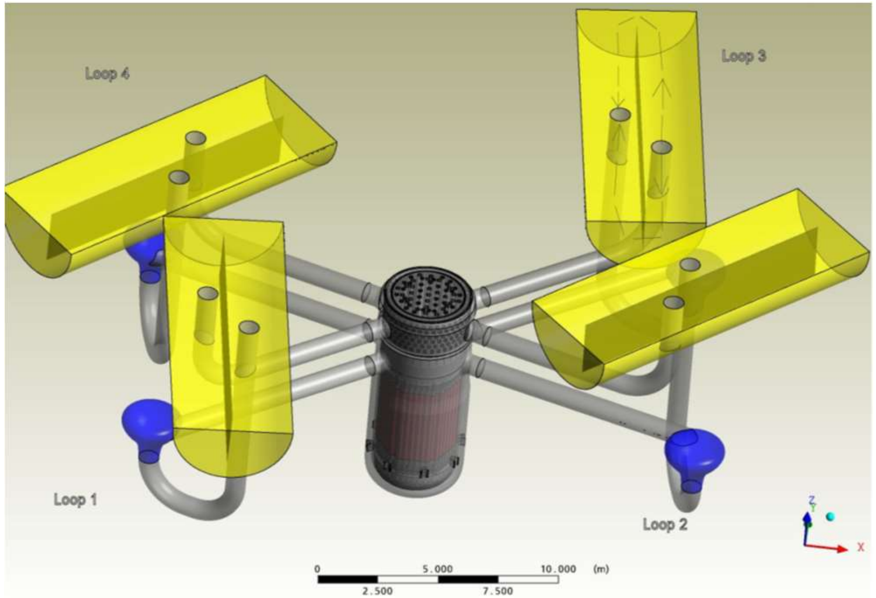
SFR-LWR (design features)

SFR



- pool type integrated design (6 immersed IHX)
- secondary loop (intermediate heat exchanger -IHX)
- low pressure
- high core power density
- flat core small active core height
- large fluid upper/lower plena

PWR



- loop type (3-4 loops, external IHX)
- high pressure
- low/medium power density
- large active core height
- small plena

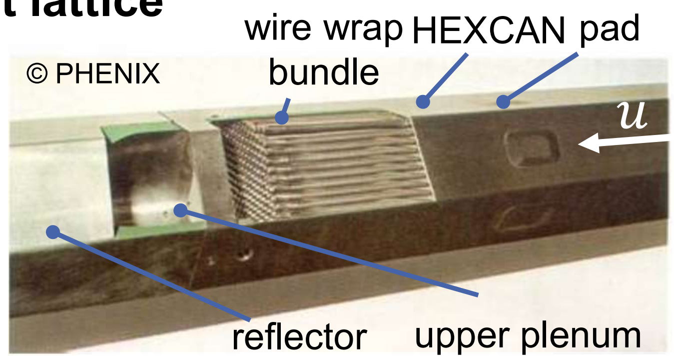
SFR-LWR- The „core“*

constitutional volume fraction [%]	SFR	PWR
nuclear fuel	37	30
coolant	**35**	**60**
steel	**24**	**9**
void	5	1
geometry [mm]	**SFR**	**PWR**
active core height H	1000	4000
pin diameter D	7.5-8.5	9.5-10
pitch/diameter P/D	**1.15-1.2**	1.3-1.4
height/diameter H/D	100	400
operational parameter	**SFR**	**PWR**
pressure p $[MPa]$	0.1	15.5
core inlet/outlet temperature T_{in}/T_{out} [°C]	395-540	285-315
core temperature rise ΔT [°K]	**145**	30
volumetric power density $\dot{q}$ $[MW/m^3]$	**300**	100
avg. linear heat rate q' $[kW/m]$	28	16

Main differences of SFR vs PWR

➡ **low thermal capacity**

➡ **tight lattice**



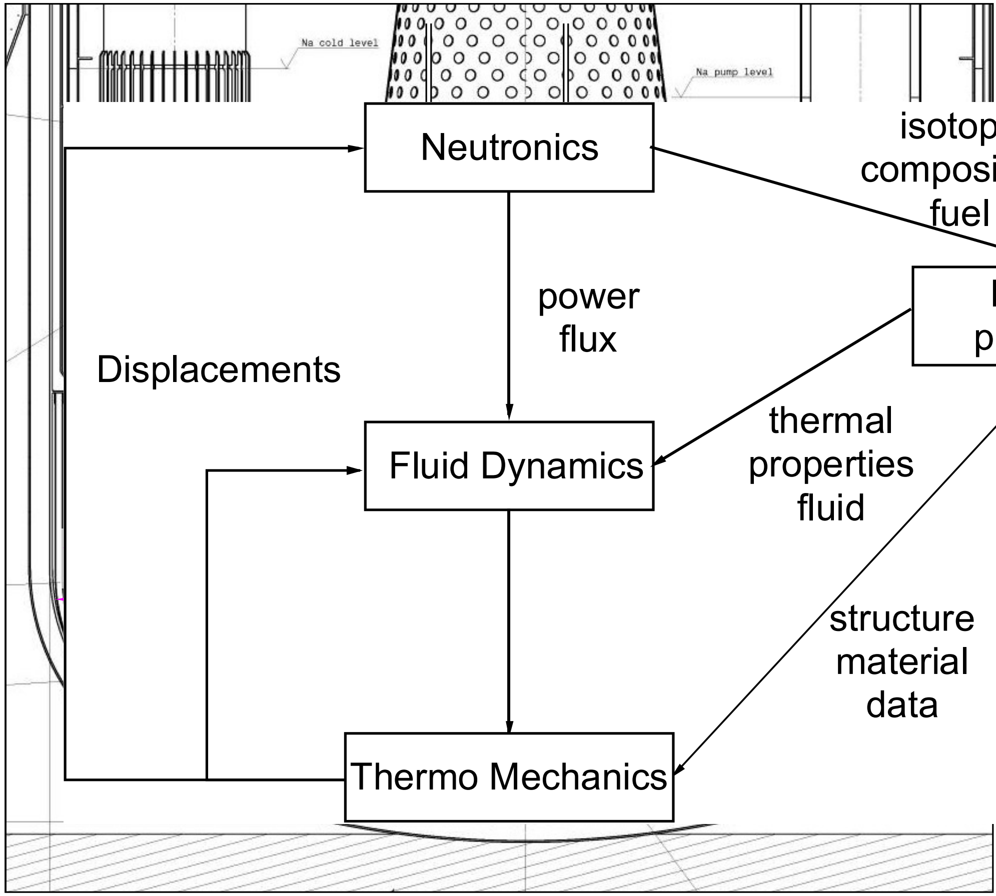
➡ **large temperature rise**
➡ **high volumetric power density**
➡ **large surface heat flux q''**

SFR- Why is the core temperature relevant ?

- **in contrast to PWR neutronic feedback does not only depend on Doppler+ and coolant density**

- ***thermal changes***
  - thermal expansion of structures
  - Impact on reactivity (+ or minus)

- **most relevant ones**
  - fuel expansion (–)
  - clad expansion (+)
  - diagrid expansion (–)
  - strongback expansion (–)
  - vessel expansion (+)
  - CR driveline expansion (+ /–)



CR=control rod expansion

SFR-PWR –Thermal hydraulics-fundamental equations & dimensionless quantities

- Conservation equations
  - mass $\nabla \cdot \vec{u} = 0$
  - momentum $\frac{d\vec{u}}{dt} = -\frac{1}{\rho}\nabla p + f + \nu \nabla^2 \vec{u}$
  - energy $\frac{dT}{dt} = \frac{\lambda}{\rho c_p}\nabla^2 T + \frac{\mu}{\rho c_p}\Phi$.

Force / energy quantity	
inertia	$u\,(\partial u/\partial x)$
pressure	$(1/\rho)\cdot(\partial p/\partial x)$
visocsity	$\nu\cdot(\partial^2 u/\partial x^2)$
gravity	g
surface tension	$\sigma/(\rho\, x^2)$
buoyancy	$(g\,\beta\ \Delta T\,)$
heat conduction	$(\lambda/\rho)\,(\partial^2 T/\partial x^2)$
heat convection	$(c_p\, u)\,(\partial T/\partial x)$

Dimensionless quantities*		Ratio X_{Na}/X_{H_2O}
Reynolds number	$Re = (u\,x)/\,\nu$	2.31
Weber number	$Wb = (\rho\, u^2 x/\sigma)$	0.25
Grashof number	$Gr = (g\,\beta\ \Delta T\, x^3)/\nu^2$	0.21
Richardson number	$Ri = Gr/Re^2$	0.04
Froude number	$Fr = u/\sqrt{g\,L}$	1.00
Peclet number	$Pe = (\rho u x c_p)/\lambda$	0.0025
Prandtl number	$Pr = (\nu \rho c_p/\lambda)$	0.0011
Fourier number	$Fo = (x^2 \rho c_p)/(\lambda\, t)$	0.0025

*assuming same $u, \Delta T$ (meaning same reactor)

SFR-PWR – thermo- physical quantities & their impact in reactor applications

- thermo-physical quantities

quantity	unit	PWR	SFR
ρ	kg/m^3	694	808
ν	$\cdot 10^7\ m^2/s$	1.19	2.7
c_p	$J/(kg\ K)$	5920	1260
λ	$W/(m\ K)$	0.539	62.9
$\beta = (1/\rho)\,\partial\rho/\partial T$	$1/K$	3.53	0.282
a	$\cdot 10^7\ m^2/s$	1.31	617.8

- dimensionless numbers in reactor core *

number	PWR	SFR
Re	$5 \cdot 10^5$	$4 \cdot 10^4$
$\boldsymbol{Pr}$	$\mathbf{0.907}$	$\mathbf{0.007}$
Ri	$3 \cdot 10^{-4}$	0.08
Fr	31	31
Pe	$4.6 \cdot 10^4$	100
Gr	$6.2 \cdot 10^{10}$	$2 \cdot 10^9$

@ nominal operation conditions for SFR core

- fully turbulent ($Re > 10^4$) ,
- forced convective flow ($Ri < 0.2$)
- tight lattices (P/D) $\rightarrow$ strong secondary flows

@ transient conditions of SFR

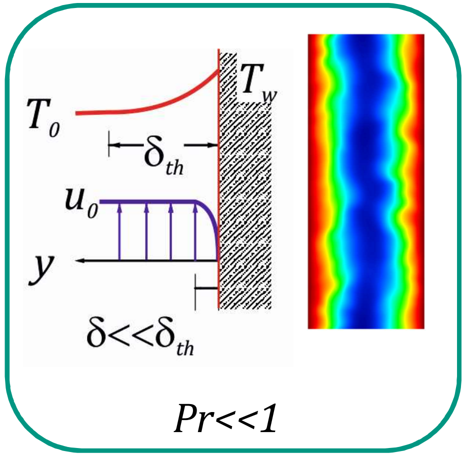
- mixed convection ($Ri > 0.2$) ,
- thermal stratification

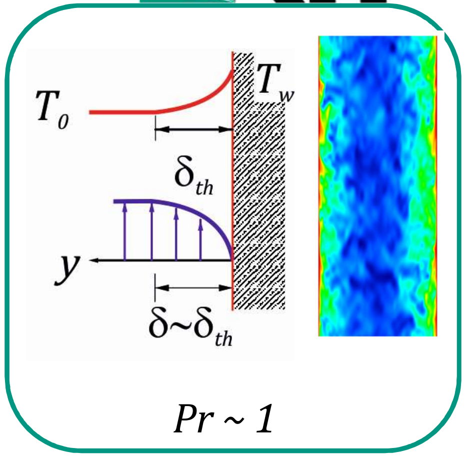
*assuming 1000MW$_{el}$ class

SFR-PWR – Prandtl number challenge

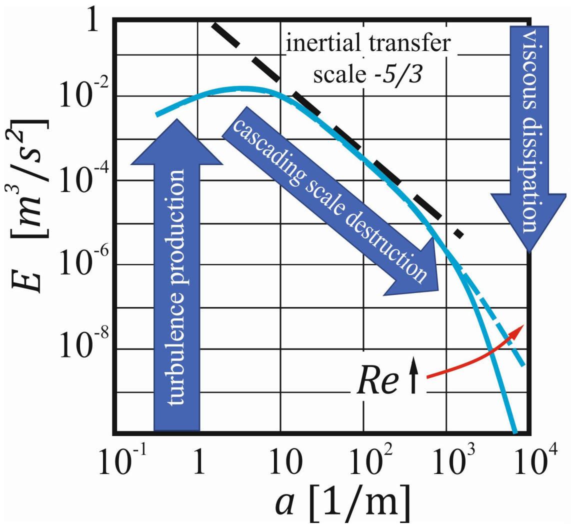
- Sodium $Pr = \frac{\nu}{a} \approx 0.007$
- separation of length scales
  - viscous scale (e.g. boundary layer) $\frac{\delta}{L} \sim \frac{1}{\sqrt{Re}}$
  - thermal scale $\frac{\delta_{th}}{L} \sim \frac{1}{\sqrt{RePr}}$

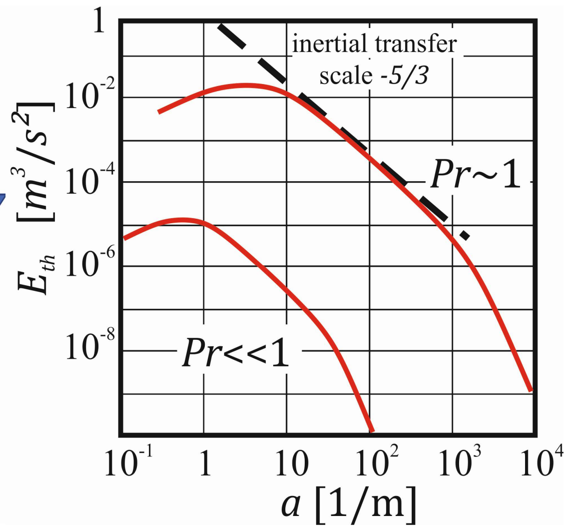
$$\frac{\delta_{th}}{\delta} \sim \frac{1}{\sqrt{Pr}} \gg 1$$





- separation of spectral scales
  - viscous eddy diffusivity (smallest scale: Kolmogorov) $l \sim \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$
  - heat diffusivity $l_{th} \sim \frac{l}{Pr^{3/4}}$

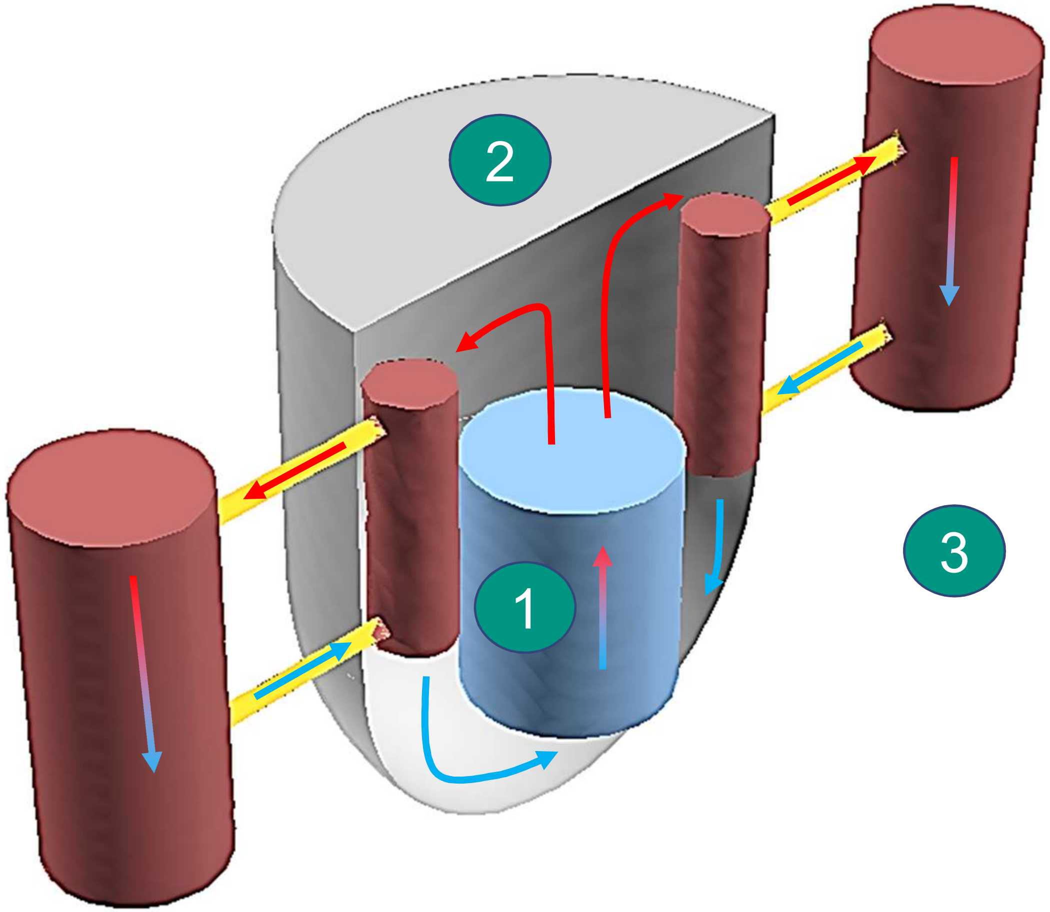




 ϵ =viscous kinetic energy dissipation

Thermal-hydraulics in reactor applications*

1. Core
   - Fuel assembly
   - Inter wrapper flow
   - Flow conditioning (inlet)
   - Boiling
   - Stratification (FA outlet)
2. Pool
   - Thermal striping
   - Mixed/buoyant convection
   - Flow mixing
   - Solidification
3. Loop dynamics
   - Multi-scale models



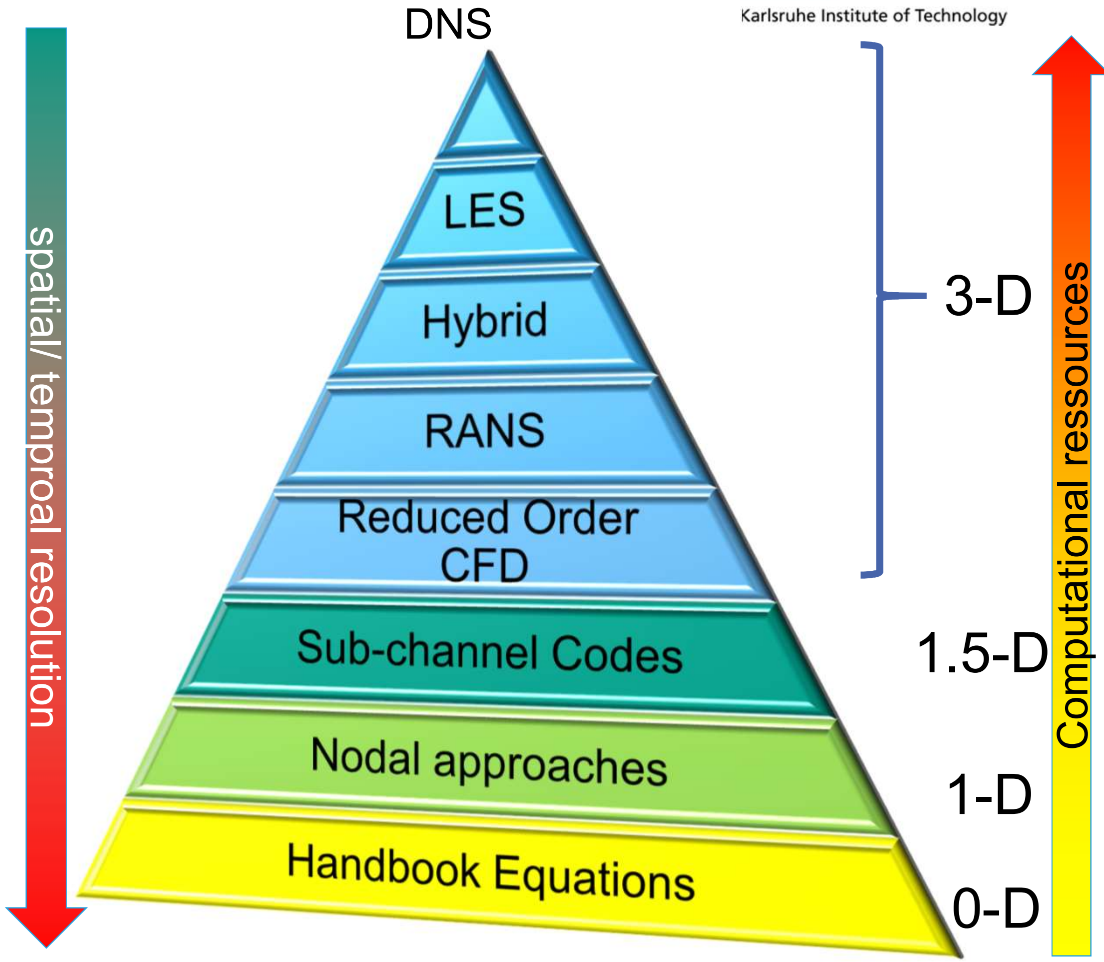
 * referring to pool type reactors

Thermal-hydraulic modelling-General

Problem adapted solution approaches

- CFD- Class solutions
  - Direct Numerical Simulation (DNS)
  - Large Eddy Simulation (LES)
  - Reynolds Averaged Navier-Stokes method (RANS)
  - Reduced Order Modelling (ROM)

- System-Thermal-Hydraulic-Simulation
  - Sub-channel approach
  - Nodal system codes
  - Handbook equations

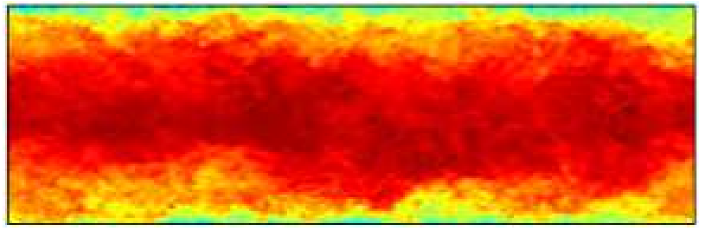


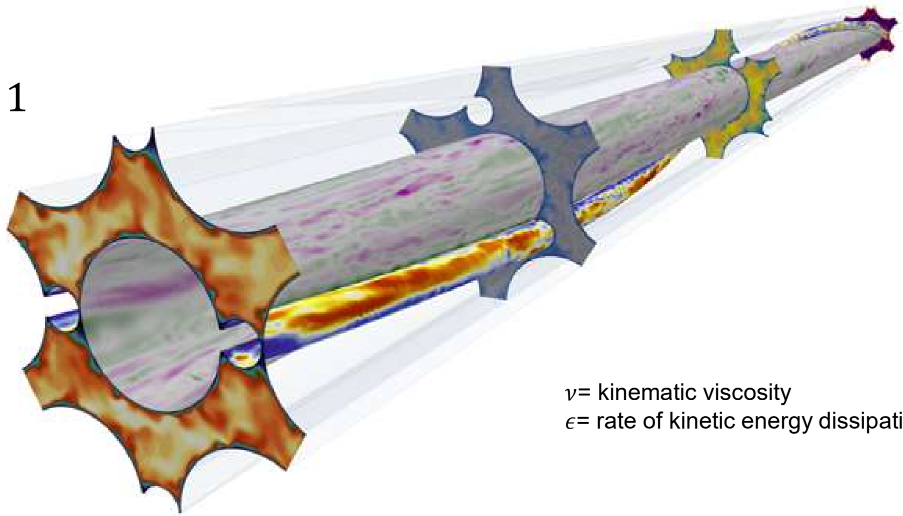
© adapted from F. Roelofs

Thermal-hydraulic modelling-CFD class

Approach of *„high fidelity solutions“*

- **DNS**
  - Resolution up to smallest eddy scale - Kolmogrov scale $l \sim \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$
  - ➡ **„quasi exact solution“**
  - high **grid resolution** requirements
    - spatial resolution h (scales L to be resolved) $N \cdot h \geq L$, but down to l requiring $h < l$
    - ➡ requiring mesh elements $\boldsymbol{N^3 \geq Re'^{9/4}}$
    - **temporal resolution** to capture vortex $C = (u' \cdot \Delta t)/h < 1$
      total time interval $\tau = L/u'$
      and number of time integration steps $L/(l\,C)$
    - ➡ total number of integration steps $\boldsymbol{\frac{L}{l} = Re'^{3/4}}$
  - No. of operations mandatory $\boldsymbol{\sim Re'^3}$
  - **DNS limited to small problems**
    - periodic boundary conditions (!) ➡ applicability
    - Reynolds number poses **large computational constraint**, but
    - indispensable for RANS turbulence model development





ν= kinematic viscosity
ϵ= rate of kinetic energy dissipation

Shams et al. (2015)

N= number of mesh points
C= Courant number
L =length scale of problem

Re' = Reynolds-number turb.scale
u'= turb. Velocity
h= spatial resolution

Thermal-hydraulic modelling-CFD class

Approach of *„high fidelity solutions“*

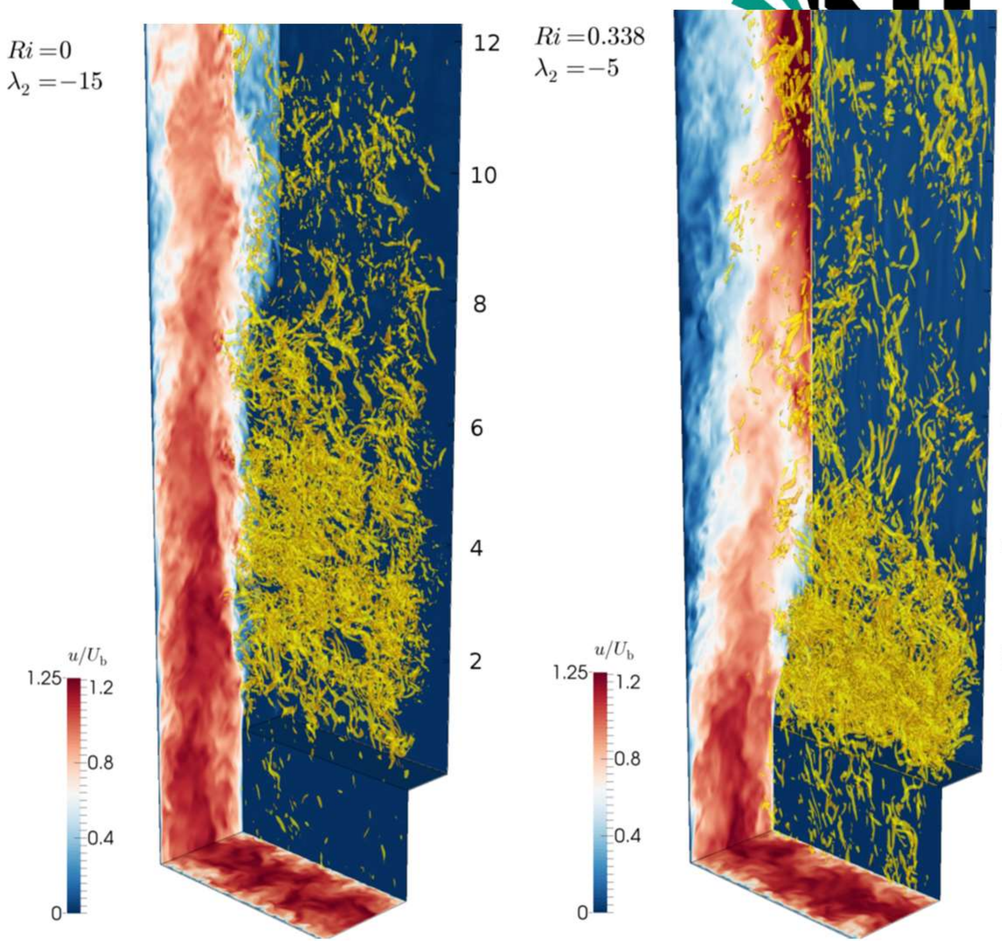
- **LES**
  - relying on self similarity (large eddies $= f\ (geometry)$)
  - smaller scales are quasi-“universal” (treated by sub grid scale model-SGS)
  - introduction of filter function
  - ➔ decomposition of velocity field $u_i = \overline{u_i} + u_i'$
  - causing virtual turbulent viscosity ν_t

LES vs. DNS

- reduced spatial resolution $h{\sim}Re$ and $h{\sim}L$
- Courant number constraint remains
- knowledge on dissipation mandtory

NOTE:

- **LES for low Pr-fluid (sodium) is quasi DNS if SGS-model dynamic respecting thermal scales**
- **be aware if $\Delta T > 30°K$ (SGS-model!!)**



Vertical backward facing step for $Ri = 0$ and $Ri = 0.38$ (Niemann et al. 2017, 2018)

Thermal-hydraulic modelling-CFD class

(U-)RANS Modelling –the working horses of CFD

- Idea – Momentum field
  - decomposition of velocity $u_i(x_i,t) = \overline{u_i(x_i)} + u_i'(t,x_i)$
  - ➡ virtual turbulent Reynolds-stress tensor $\frac{\partial}{\partial x_j}\left(\rho\overline{u_i'u_j'}\right)$
  - model assumption (GDH): (representation by mean flow) $\overline{u_i'u_j'} = \varepsilon_m^{ij}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)$

ε_m^{ij} =eddy diffusivity of mass (**tensor !**)

- spatial resolution similar as LES for low Re-models
- temporal resolution at discontinuities Courant number (C) limited

- solution classes:

order	isotropic	anisotropic	no. transport eq.
1st	gradient models, eddy diffusivity		
	mixing length	mixing length	0
	$k-l$		1
	$k-\varepsilon, k-\omega$, SST	Cubic $k-\varepsilon$, EARSM, V2f	2 (3)
2nd		RSM	6+2

GDH= gradient diffusion hypothesis
L =length scale of problem h= spatial resolution

Thermal-hydraulic modelling-CFD class

RANS Modelling –the working horses of CFD

- Idea heat
  - Reynolds decomposition yields turbulent heat flux $\rho c_p \overline{u_j' T'}$
  - introducing similarly an eddy diffusivity of heat $\overline{u_j' T'} = \varepsilon_H^j \left(\frac{\partial T}{\partial x_j}\right)$ ε_H^j =eddy diffusivity of heat (**vector !**)
  - turbulent Prandtl-number $Pr_t = f(Re, Pr, y/R\,) = \frac{\overline{u'v'}}{\overline{v'T'}} \cdot \frac{\partial T/\partial y}{\partial u/\partial y}.$
- Solution classes:

order	isotropic	anisotropic	No. transport eq.
0	look-up tables local turbulent Pr_t		
1st	mixed wall law approaches	algebraic heat flux models (AFHM)	1+ (2)
		$k-\varepsilon-k_\theta-\varepsilon_\theta$, TMBF	4

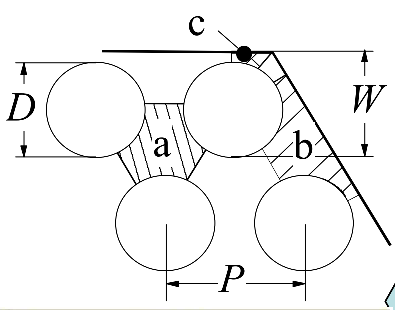
- Reynolds Analogy: $\overline{u_j' T'} = \varepsilon_H^i \frac{\partial T}{\partial x_j} \approx \frac{\varepsilon_M}{Pr_t} \frac{\partial T}{\partial x_j}$ assuming $\boldsymbol{\varepsilon_M / Pr_t \approx const.}$, despite different statistics of u- and $T-$ field, anisotropy (most codes use $Pr_t = 0.9$)

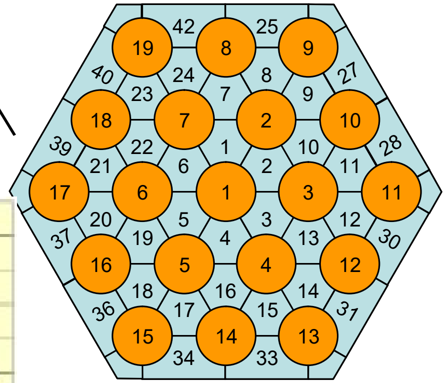
Thermal-hydraulic modelling-System thermalhydraulics

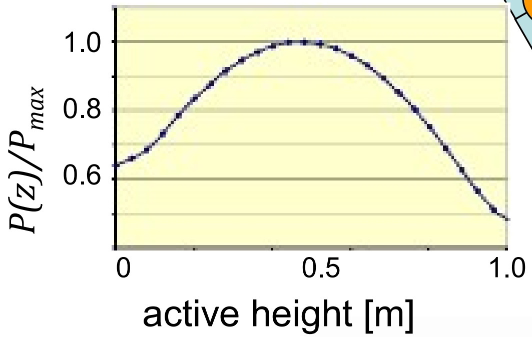
- Most complex STH: Core –Treatment SA-wise

Approach:

- **Meshing of SA**
  - **Lateral direction**
    - triangular (Δ), rectangular shaped (□), corner sub-channels,
  - **Axial direction**
    - mostly equidistant
- **Power from neutronics** ➡Reconstruction of power distribution
  - ➡ 3 pins for Δ channel P_{Δ}=3·1/6 P_{pin},
  - ➡ 2 pins for □ channel $P_{\square}$=2·1/4 P_{pin}
  - ➡ 3·1/6 P_{pin} corner channel



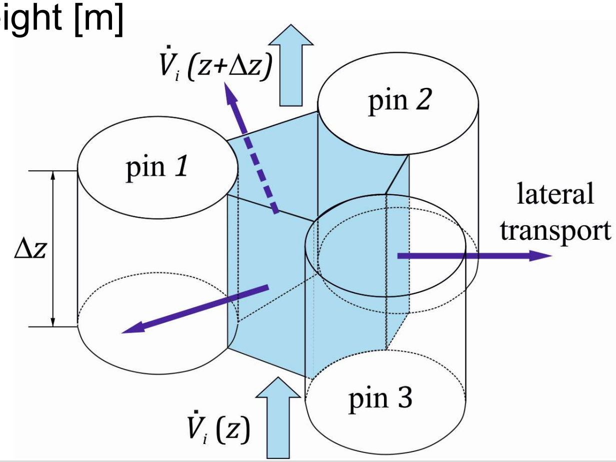




Computations

- mass conservation $\dot{V}_{SA} = \sum \dot{V}_i$
- flow/pressure BC

$$\dot{V}_i = \frac{A_i \cdot d_{h,i}^{\beta}}{\sum_{i=1} A_i \cdot d_{h,i}^{\beta}} \cdot \dot{V}_{SA}$$



Result

- different flow rates in-subchannels $\dot{V}_{\square} > \dot{V}_{\Delta}$ ➡consequence W/D adaption

d_h =hydraulic parameter
β=lateral exchange coefficient
A_i=cross-sectional area

Thermal-hydraulic modelling-System thermalhydraulics

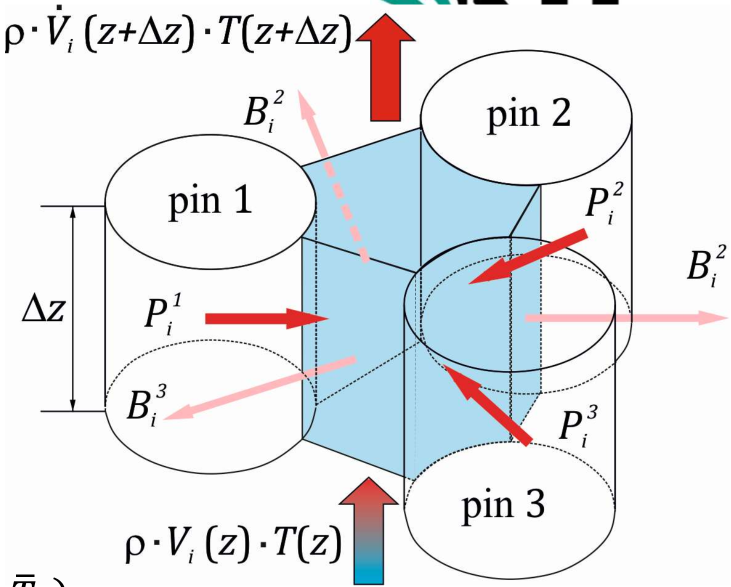
- Most complex STH: Core –Treatment SA-wise

Approach:

- **assume stable axial flow**

Computations

- mean temperature $\bar{T}$ $\bar{T} = \frac{T(z)+T(z+\Delta z)}{2}T$
- power in SC P_i : $P_i = \sum_j P_i^j$
- transfer coefficients between adjacent SC B_i^a, transfer SC to boundary B_i^b
- energy balance $c_p \cdot \dot{V}(z) \cdot \big(T(z+\Delta z) - T(z)\big) = P_i - \sum_a B_i^a(\bar{T}_i - \bar{T}_a)$- $B_i^b(\bar{T}_i - \bar{T}_b)$



Challenge: determination of transfer coefficients B_i^*

- solution for border (thermal BC to solid boundary) $B_i^b = \alpha \cdot A_b \cdot \Delta z + P_b$
- lateral exchange modelled by superposition of different effects
  - heat transfer due to wires $B_i^{'}$ (by spiral flow motion)
  - heat transfer due to thermal conduction $B_i^{''}$ (by spiral flow motion)
  - heat transfer due to turbulent mixing $B_i^{'''}$ (dissipation effects)

SOLUTION:

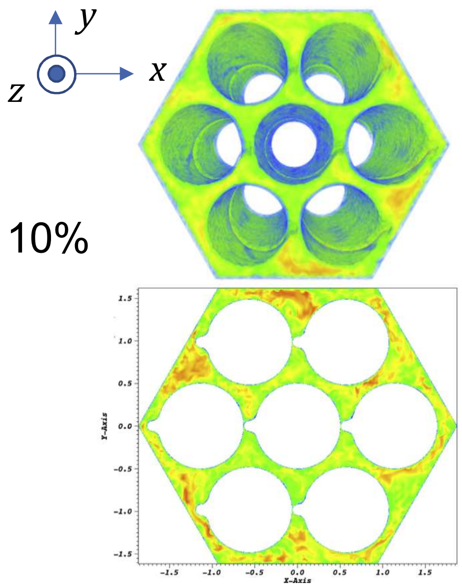
- **Reynolds-Analogy** (hydraulic diameter concept) with experimentally determined coefficients
- **correlations from experiments**

α=heat transfer coefficient
P_b=heat deposited in border
A_b=Area of Border

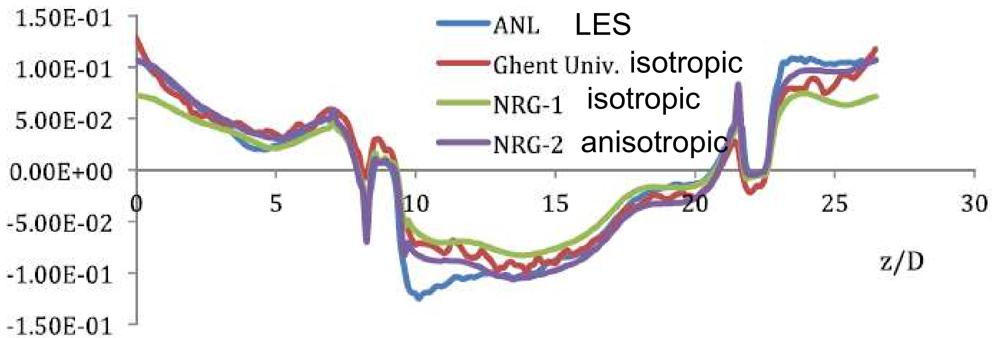
Applications- CORE

Momentum transfer- SA

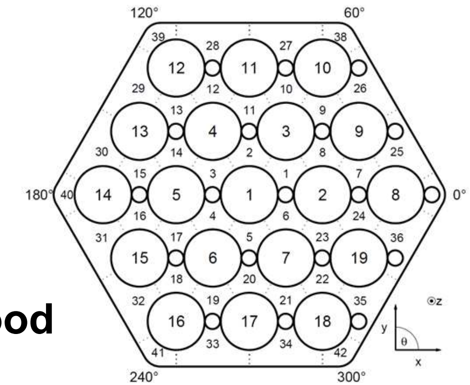
- **Hydraulic benchmark**
  - 7-pin bundle
  - RANS vs. LES deviations max. 10%
    - streamwise velocity
    - cross-flow

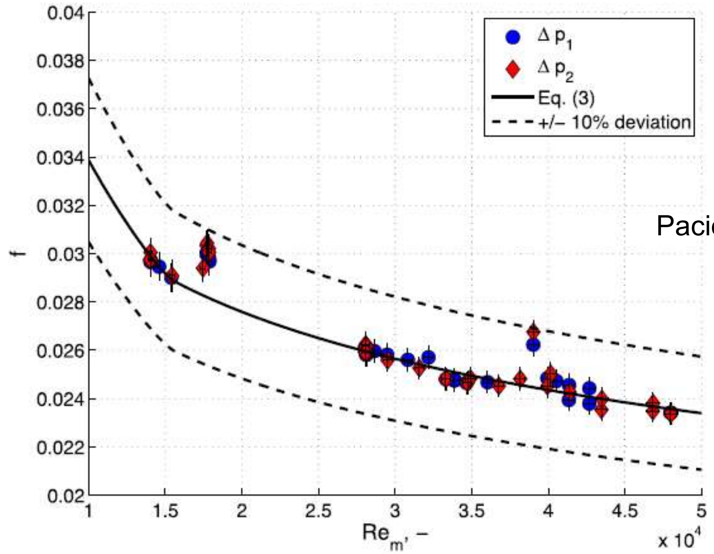


Merzari et al. (2016)



- **KALLA**
  - 19-pin bundle
  - Measurement vs. STH correlations
  - Cheng and Todreas (1986): RMS = 3.8%, all data within 8%





Pacio et al. (2016)

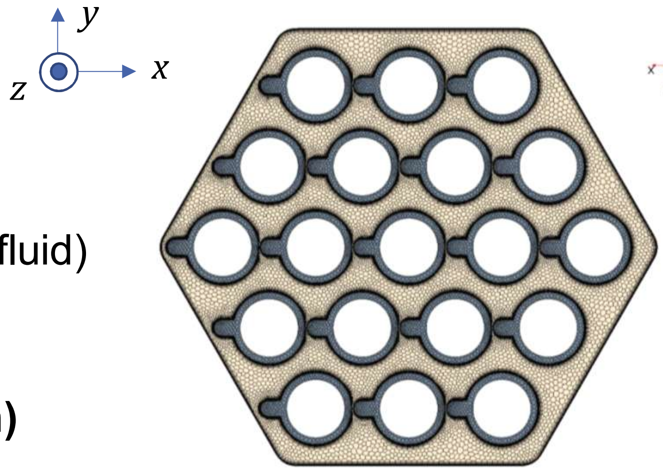
➡ **for skilled user STH is similarly good as CFD (important for design)**

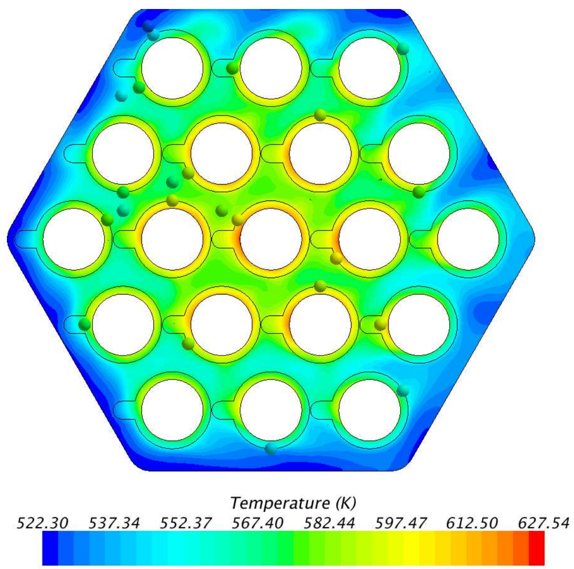
Applications- CORE

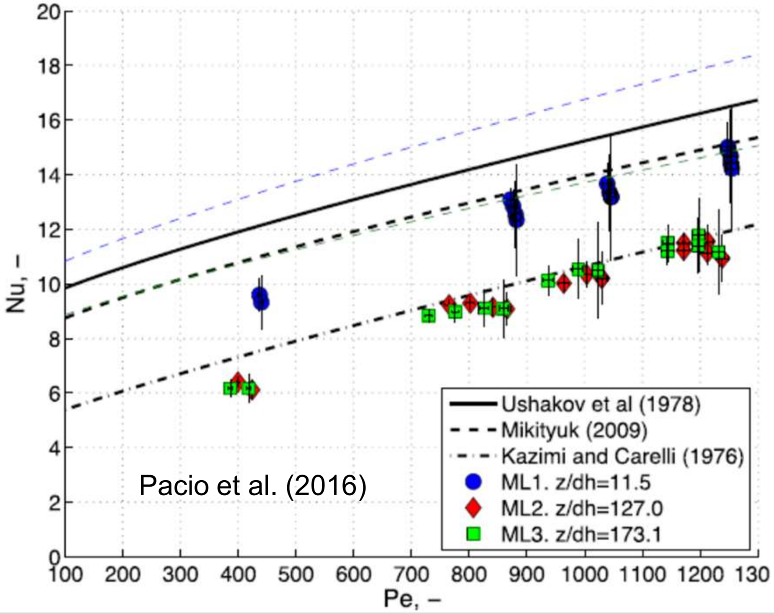
Energy Transfer- SA

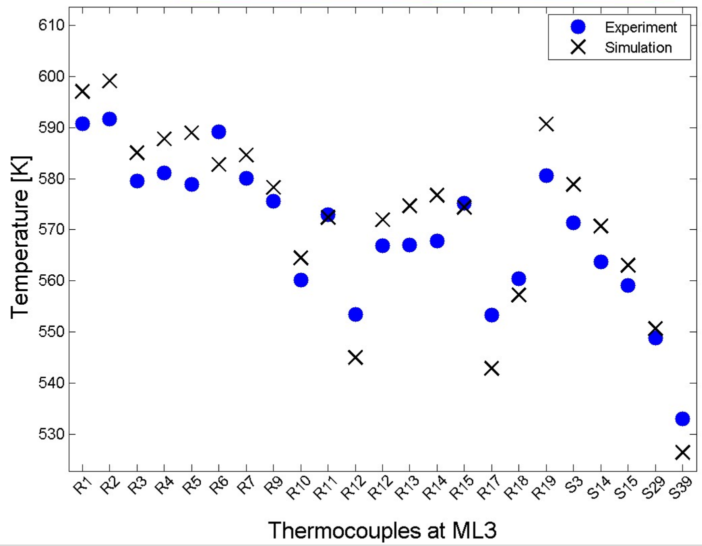
- **KALLA Experiments**
  - Computational Mesh ($4 \cdot 10^7$ solids $1.6 \cdot 10^8$ fluid)
  - local Pr_t Approach, $Re = 3 \cdot 10^4$

- local deviations $\Delta \boldsymbol{T}/\boldsymbol{T} \leq \mathbf{13\%}$ **(end of length)**
- Nusselt number deviation $\boldsymbol{Nu}\sim\mathbf{20\%}$ **to CFD**
- Nusselt number deviation to **best correlation** $\sim\mathbf{3\%}$ **others 20%**





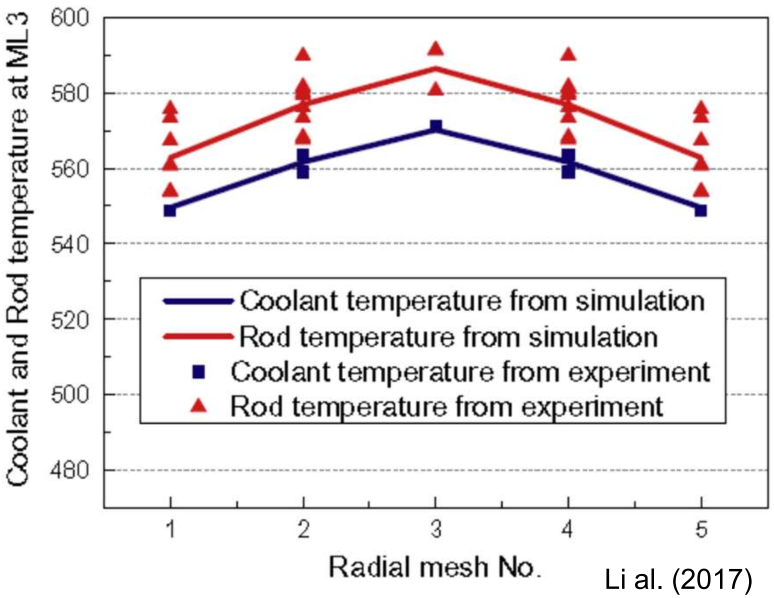




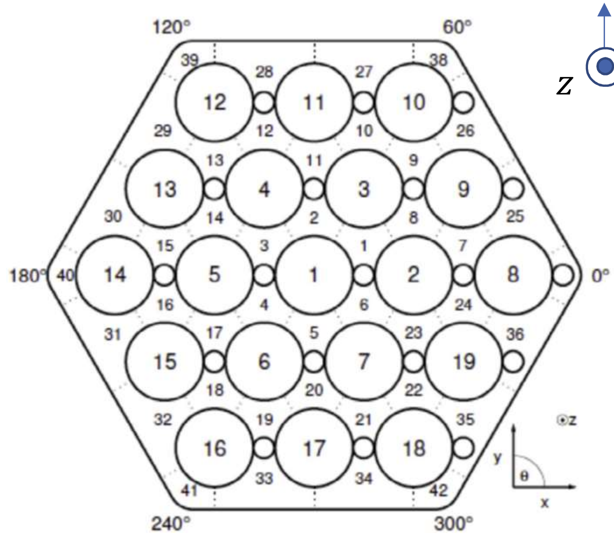
Applications- CORE

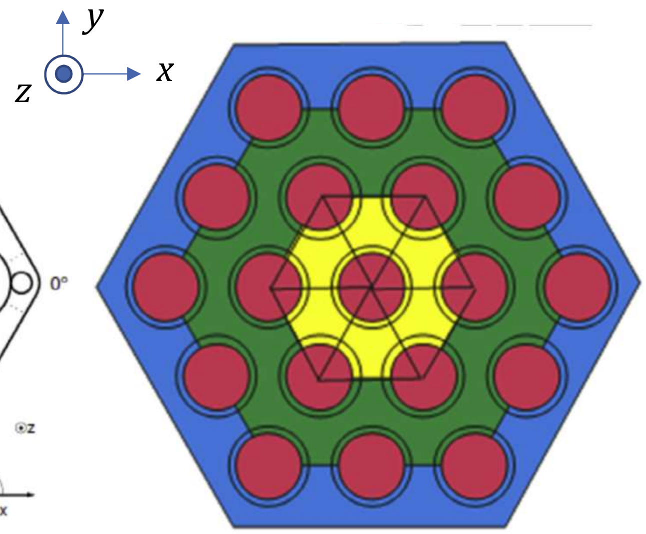
- Energy Transfer- SA
- **Performance of CFD vs. STH**
  - 3 sub-channel grous,
  - 46 cells planar, 128 axial ➡ $\sim 6 \cdot 10^3$ cells

- **STH predictions are in range of 20% as well !!!**



Li al. (2017)





MESSAGE :

- CFD (by qualified used) accuracy of 10% for $u-$, $T-$ field with high local resolution
  - Identification of hotspots (recirculation areas)
  - Lateral exchange coefficients
- Similar quality obtained for mean bulk values by STH (best agreement for Δp Rehme correlation, T –field and $Nu-$ Kazimi-& Carelli) requiring experienced input, lot of pre-emptive know-how
- **What about mixed & buoyant convection ?**

Applications- CORE -conclusions

- **some comments on SA -bundle flows**
  - sparse data matrix for sodium
  - even poorer in conjunction with wire wraps
  - inconsistent documentation of experiments (power balance, flow state –forced –mixed-buoyant)
  - low degree of instrumentation, poor consistency
  - contradictory measurement data (limited to scalars such as p , T)

➡ both CFD & STH quality depend essentially on USER know-how

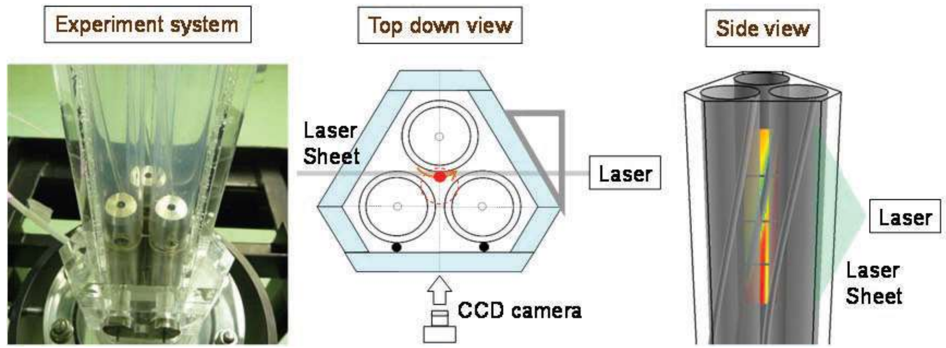
- **Benchmarks on SA -bundle flows are rare**
  - mandatory to proof local flow distribution
    - ➡ air water sufficient (Kamide, 2016)
    - ➡ without „healthy" u-field satisfactory acceptable T-field not achievable
  - improvement of local measurement techniques in sodium
    - ➡ spectral quantities of T-field to get data on $\overline{T'^2}$ and $\varepsilon_{\overline{T'^2}}$
    - ➡ evaluation of onset of transition of flow regimes (forced→mixed convection- mixed → buoyant convection)

➡ **well posed benchmarks required**

Overview of experiments for fuel assemblies with wire wraps.

Experiment	Fluid	No. of Pins	*Re*
Collingham et al. (1970)	Sodium	7	5000–50,000
Fontana (1973), Wantland et al. (1976)	Sodium	19	n.a.
Ohtake et al. (1976)	Air	37	6800–15,000
Lorenz and Ginsberg (1977)	Water	91	9000–24,000
Chiu (1979)	Water	37	3000–14,000
Fenech (1985)	Water	61	100–11,000
Roidt et al. (1980)	Air	217	12,000–73,000
Engel et al. (1980)	Sodium	61	500–15,000
Chun and Seo (2001)	Water	19	100–60,000
Choi et al. (2003)	Water	271	1100–78,000
McCreery et al. (2008)	Mineral oil	7	22,000
Sato et al. (2009)	Water	7	6000
Tenchine (2010)	Air	19	3000–28,000
Prakash et al. (2011)	Water	217	75,000

extracted from Roelofs et al. (2015)



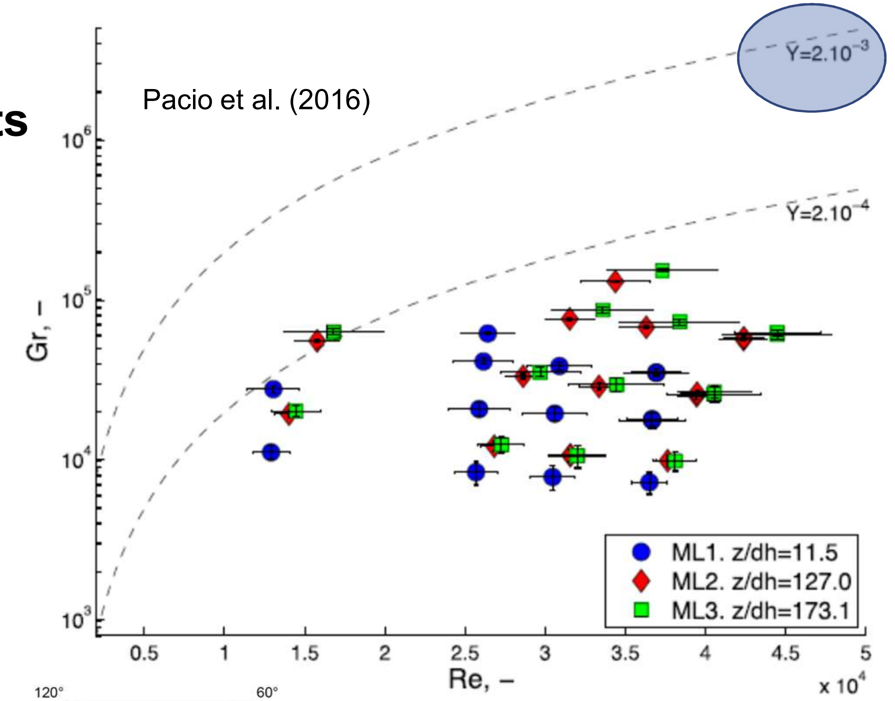
Kamide et al. (2016)

Applications- CORE -conclusions

- a **clean experiment requires evaluation of buoyant effects** e.g. analysis by dimensionless quantities $Y = Gr/Re^2$ (according to Jackson (1983) onset of mixed convection occurs if $Y \geq 2 \cdot 10^{-3}$)

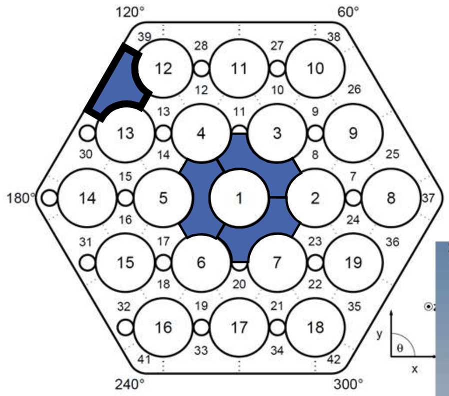
➡ **well documented mixed& buoyant experiments absent !**

- improvements require closed definition of benchmarks by model developers&simulations **AND** experiments (starting already in the definiton of the experiment along preparation, up to execution & analysis)

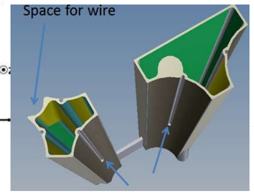


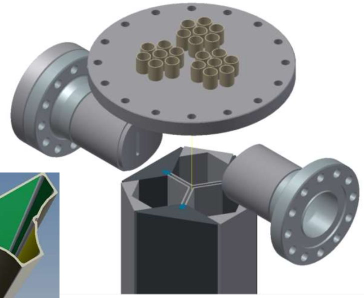
Many aspects not adressed in this context

- impact of pin deformation on flow field
- flow induced vibrations
- inter-wrapper flow (sodium-Kamide, 2001- LBE- Pacio 2019)
- flow blockage (partial, total, porous ➡ sodium-Raj Velusami, 2016, LBE-Pacio et al. 2018)
- sodium boiling (as it may occur in ULOF – Khafizov et al. 2015)



flow blockage



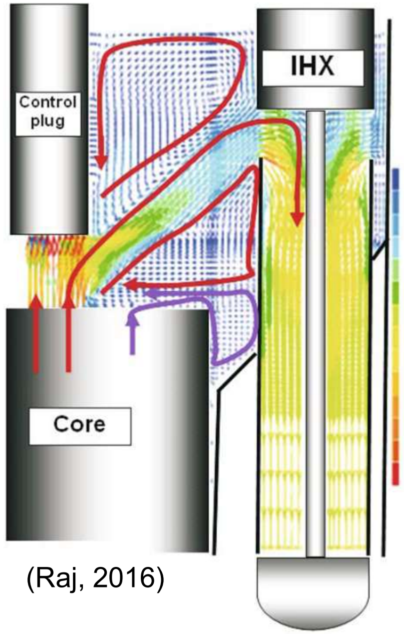


inter-wrapper- flow

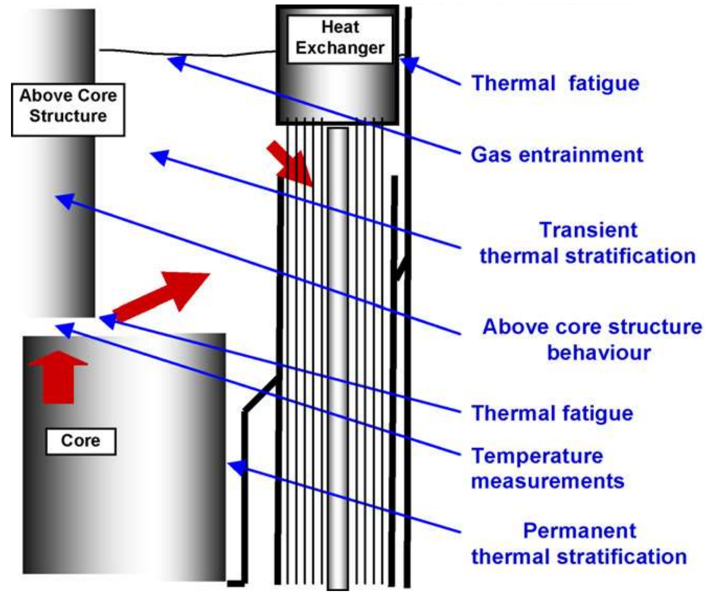
Applications- Pool

- **Relevance for reactor licensing**
  - **normal operation**
    - thermal inertia (ramp-up/shut down)
    - reduced power
    - particle/gas transport
  - **operational transients**
    - component failure (pump, HEX)
    - loss of flow (LOFA
    - loss of heat sink (LOHS)
    - decay heat removal (DHR)
- **Thermal-hydraulic issues**
  - **core coolability**
    - Heat transfer, Overcooling (freezing)
    - Transient flow behaviour, natural circulation
  - **structural loads**
    - thermal stratification/thermal fluctuations
    - flow mixing, flow separation
    - flow induced vibrations
    - coolant level fluctuations
  - **Gas/vapour/particle transport**
    - gas entrainment/fission product transport

Upper plenum

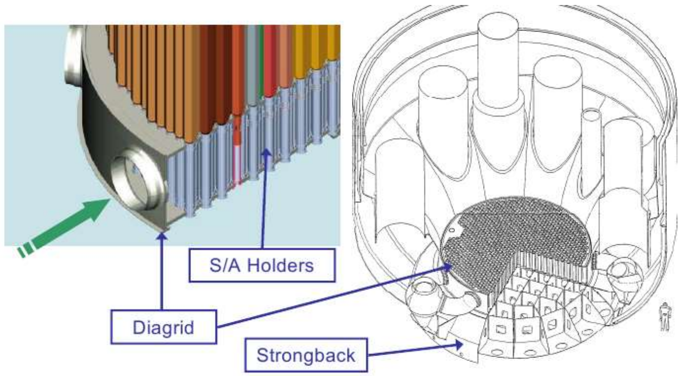


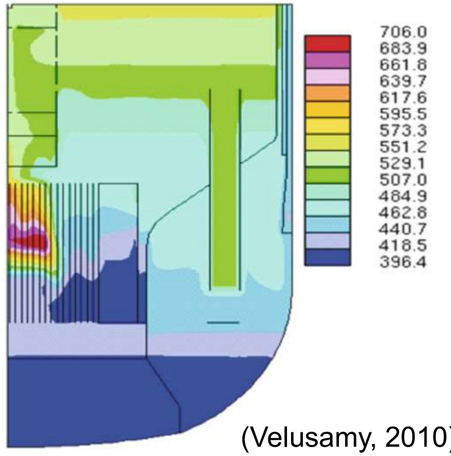
(Raj, 2016)



(Tenchine, 2010)

Lower plenum

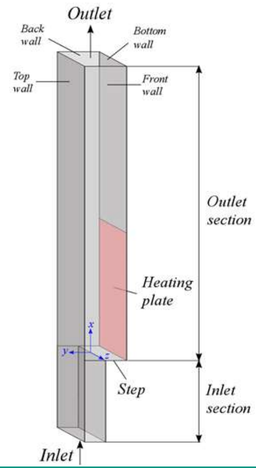


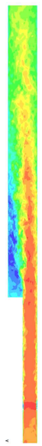


(Velusamy, 2010)

Applications- Pool

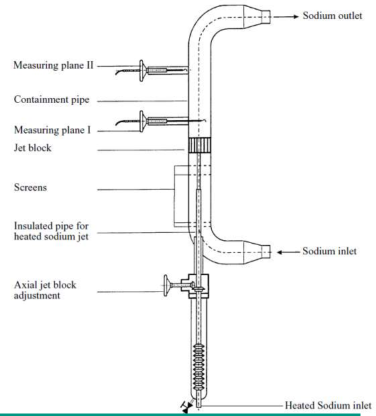
T.Schaub
(31st March 2021)





Yu (2017)

Knebel (1994)



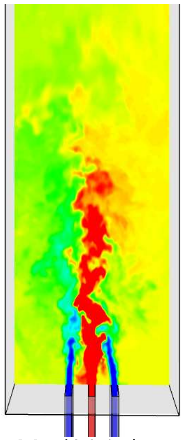
solution strategy

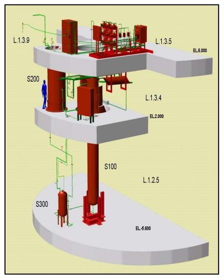
- **separate-effect tests (numerical+experimental)**
  - referring to single physics phenomenon (e.g. mixing, thermal striping, flow separation,.....)
  - intensive instrumentation/ refined meshing

➡ model tuning/improvement, transport characteristics

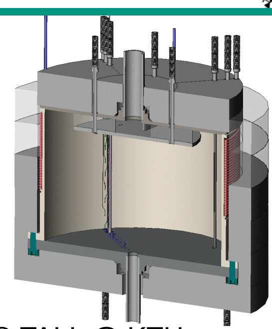
- **scaled integral test (requiring experiment)**
  - Combination of phenomena in scaled set-up
  - Utilization of dimensional analysis (model fluids)

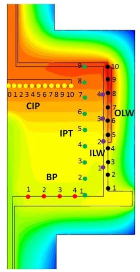
➡ interaction time scales (STH- CFD coupling)





© CIRCE @ ENEA

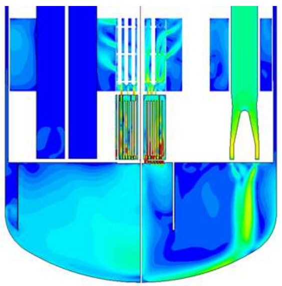




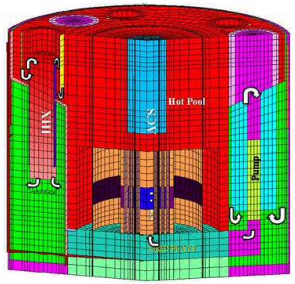
© TALL @ KTH

- **prototype experiments w/o reactor**
  - prototypical conditions (length scales, fluid, mimicing feedbacks, active components
  - limited instrumentation,large effort

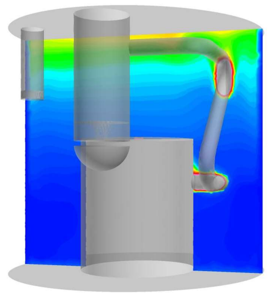
➡ **reliable, extrapolable scaling** ➡ **licensing**



ESCAPE-LBE



IAEA-PHENIX-benchmark

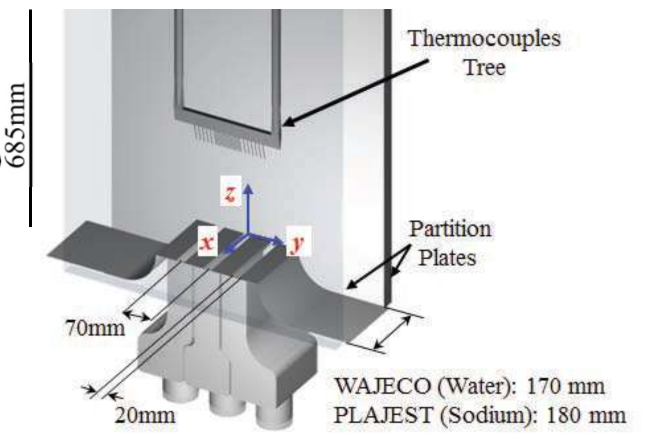


EBR-II Sodium

Applications- Pool –separate effects (SE)

Thermal mixing of cold & hot jet (Water vs Sodium)

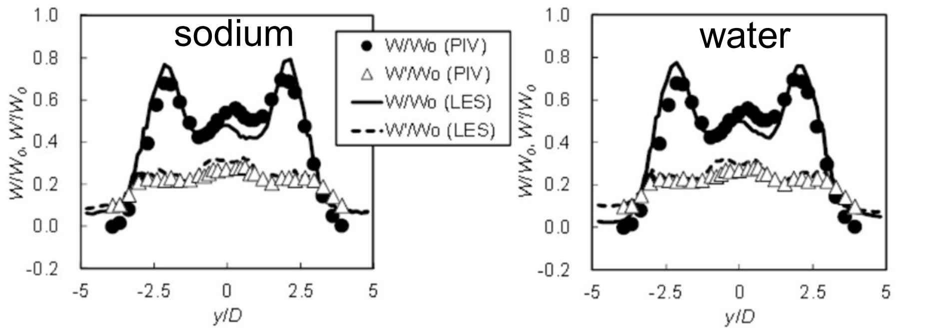
WAJECO & PLAJEST
(Kobayashi et al., 2015,
Tanaka 2016, and Yu 2017)



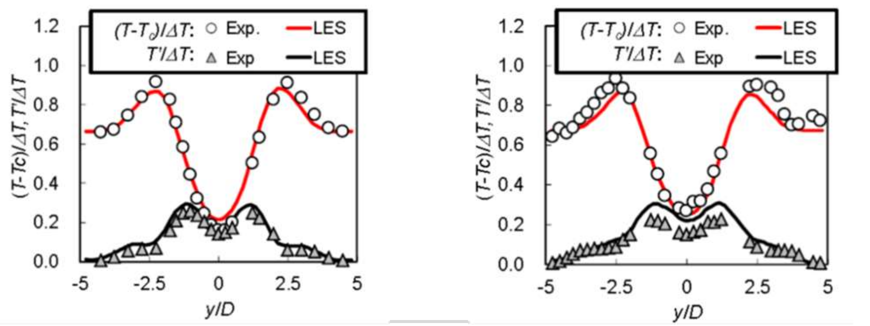
- **two hot jets neighboring cold jet**
  - relevant dimensionless quantity –densimetric Froude number
    $Fr = (M \cdot \bar{u})/(B \cdot d)$
    $Fr > 10^3$ inertia dominate, $Fr \approx 400$ mixed, $Fr < 100$ buoyant)
  - simulation: LES ($1.2 \cdot 10^7$cells), URANS ($3 \cdot 10^6$cells), RANS ($3 \cdot 10^5$cells),

$Fr \approx 600$

- good agreement of sodium & water experiments ($z/D = 5$)
  for mean ($\bar{u}/\bar{u}_0$) and fluctuating velocity part ($\overline{u'}/\bar{u}_0$)
- self-similarity of momentum profile (coincides with Knebel 1994)



- qualitative and quantitative agreement of mean temperature ($\bar{T}$)
  with LES for both water & sodium
- as expected about 25% less temperature fluctuations ($\overline{T'}/\Delta\bar{\bar{T}}$)
  in sodium compared to water, but
- good qualitative & quantitative agreement
- **is now all fine ?**



Momentum flux $M = \int (\bar{u}_j^2 - \bar{u}_a^2) dA$

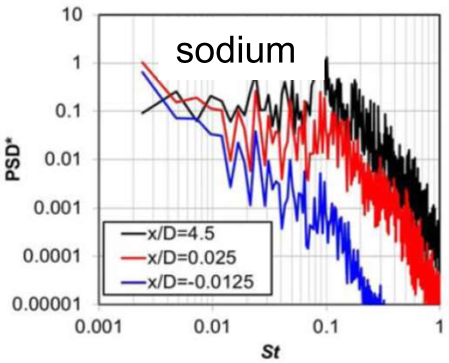
Buoyancy flux $B = g \int \frac{\rho_a - \rho(\bar{T})}{\rho(\bar{T})} dA$

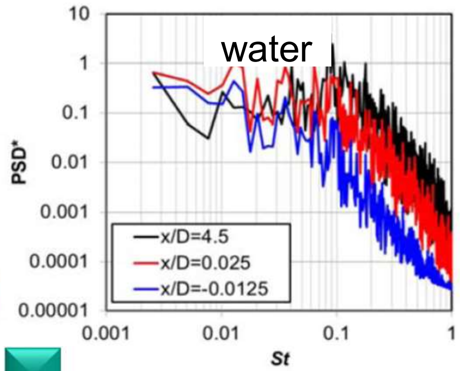
Applications- Pool –separate effects (SE)

Thermal mixing of cold & hot jet (Water vs Sodium)

- **two hot jets neigboring cold jet ($Fr \approx 600$)**

- spectral behaviour of temperature fluctuations ($\overline{T}'/\Delta\overline{\overline{T}}$) shows already at small x/D significant deviations

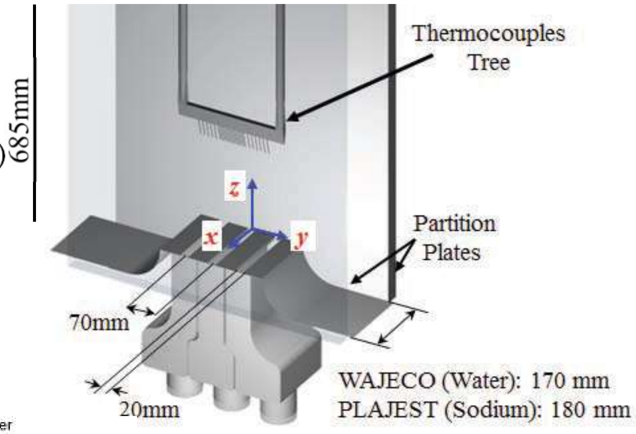


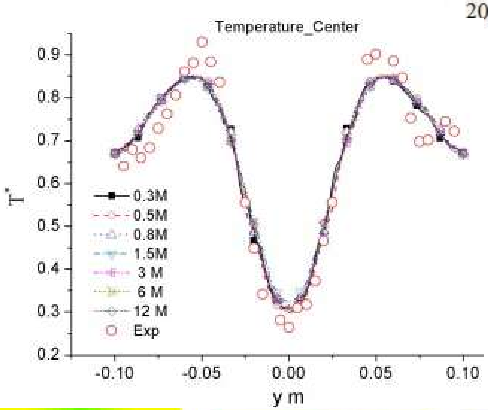


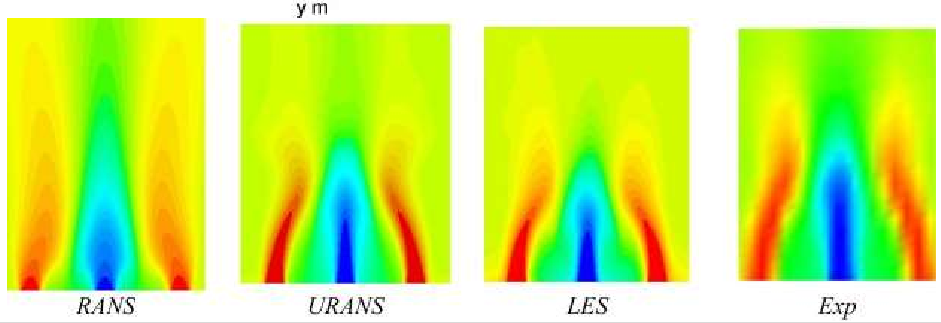
- downstream deviations experiment vs. simultation for temperature grow (not to be compensated by increased simulation mesh number)

- **temperature field in mean distribution captured by LES, RANS, URANS) with accuracy of 15-20%**

WAJECO & PLAJEST
(Kobayashi et al., 2015,
Tanaka 2016, and Yu 2017)





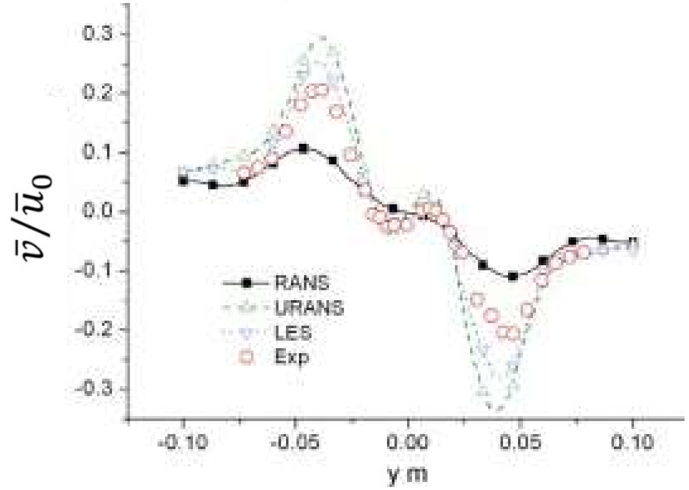


Applications- Pool –separate effects (SE)

Thermal mixing of cold & hot jet (Water vs Sodium)

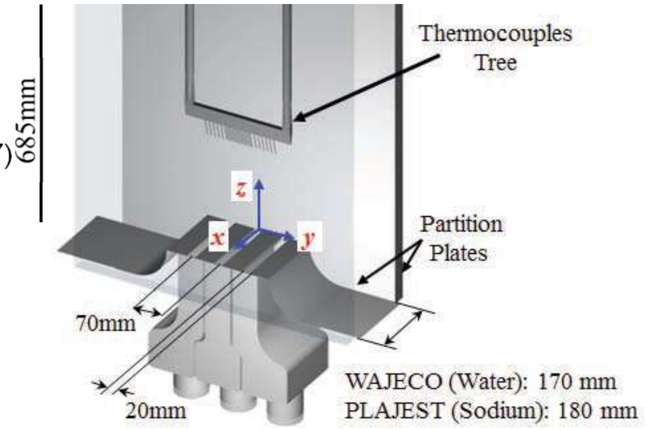
- **Two hot jets neigboring cold jet** $(Fr \approx 600)$

- exact calculation of momentum field essential

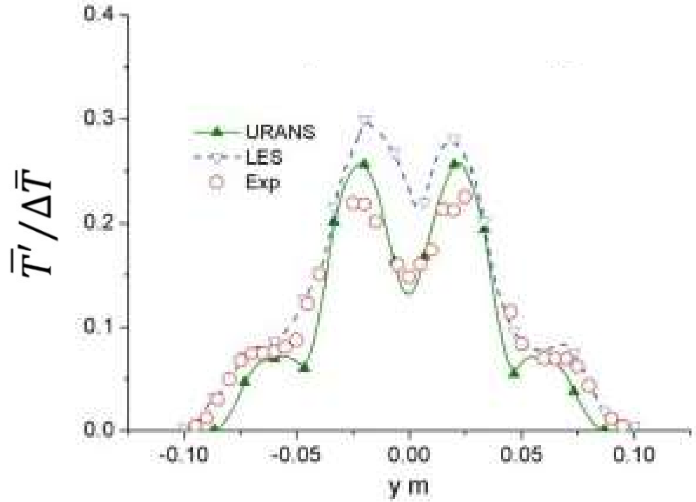


- use of LES improves congruence of exp./sim. considerably !!!!
- **SE –test indispensable to identify order of magnitude deviations likely to occur, thus**
- **allowing CFD tools to act credibly for full pool simulations with assessments for DESIGN & SAFETY !!!!**

WAJECO & PLAJEST (Kobayashi et al., 2015, Tanaka 2016, and Yu 2017)



- but still temperature fluctuations (eddy diffusivity of heat not captured fully 15-20%)
- unfortunately no measurement error

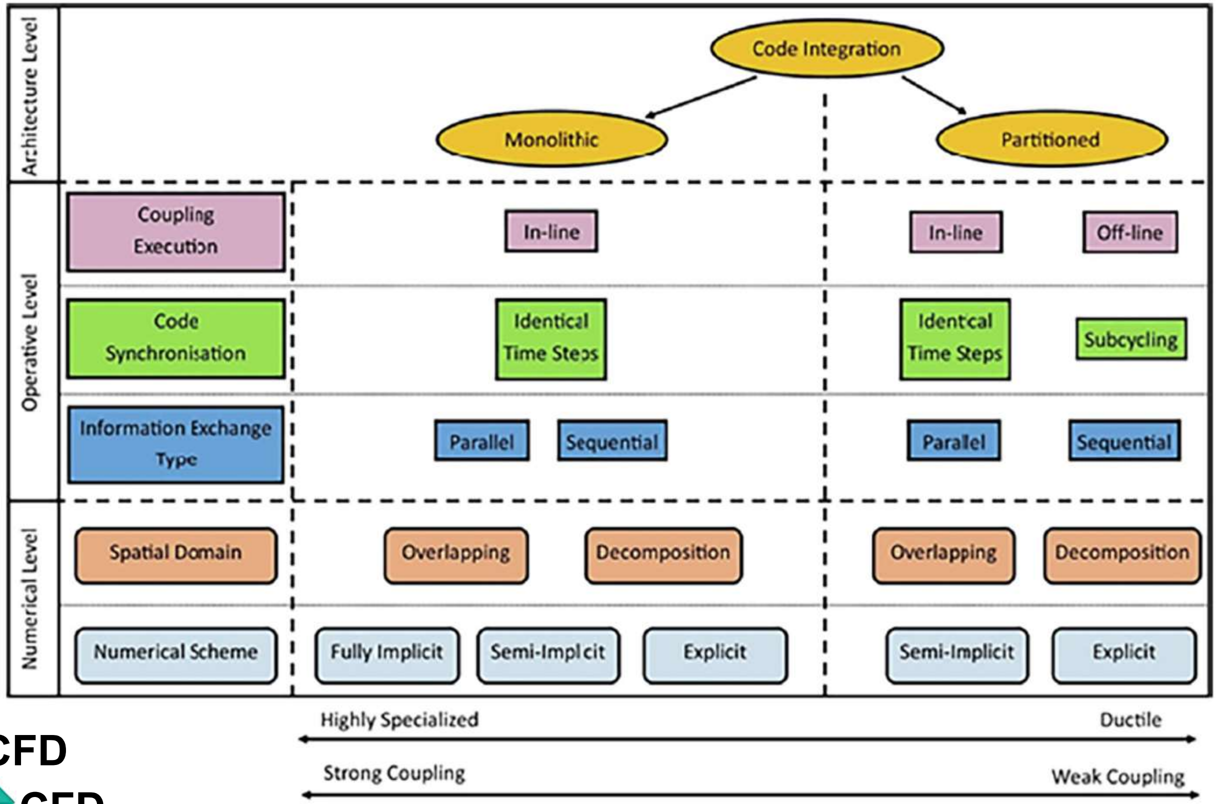


Applications- Pool – coupled STH –CFD

strategy to calculate multi-scale phenomena (adopted from LWR's)

- decompose reactor in several domains to be treated by different tools
  - external loops treated
    1D STH tools
    (RELAP, TRACE, CATHARE,ATHLET, ASPEN,……)
  - provision of boundary conditions (p, T, $\dot{Q}$)
    and time scale Δt
  - depict core internals as much as possible by reduced order models
    - porous body modelling of
      e.g. HEX or core (to account for 3D flow)
    - subchannel analysis of SA flow
      $1{,}5D$ to attain correct N-TH feedbacks
    - pumps as momentum source
      (Δp, vorticity ω – inviscid approach)

Pucciarelli et al. 2021, Zhang 2018



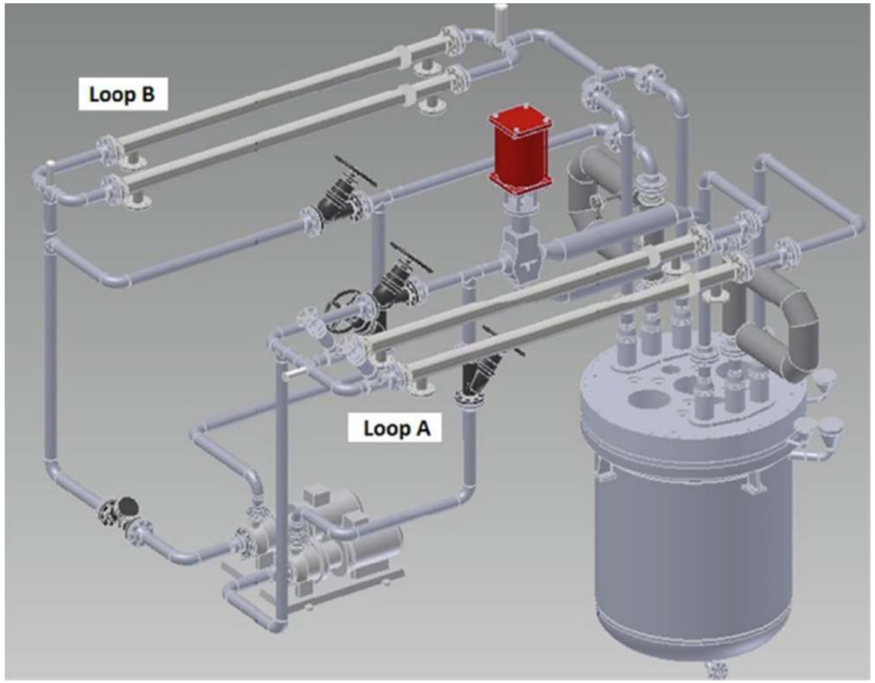
- **reducing 3D problem to the free pool only by CFD**
- **evaluate appropriate coupling scheme STH ⟺ CFD**
  (code hierarchy, synchronisation-communication, domain treatment, numerics)

Applications- Pool – coupled STH –CFD

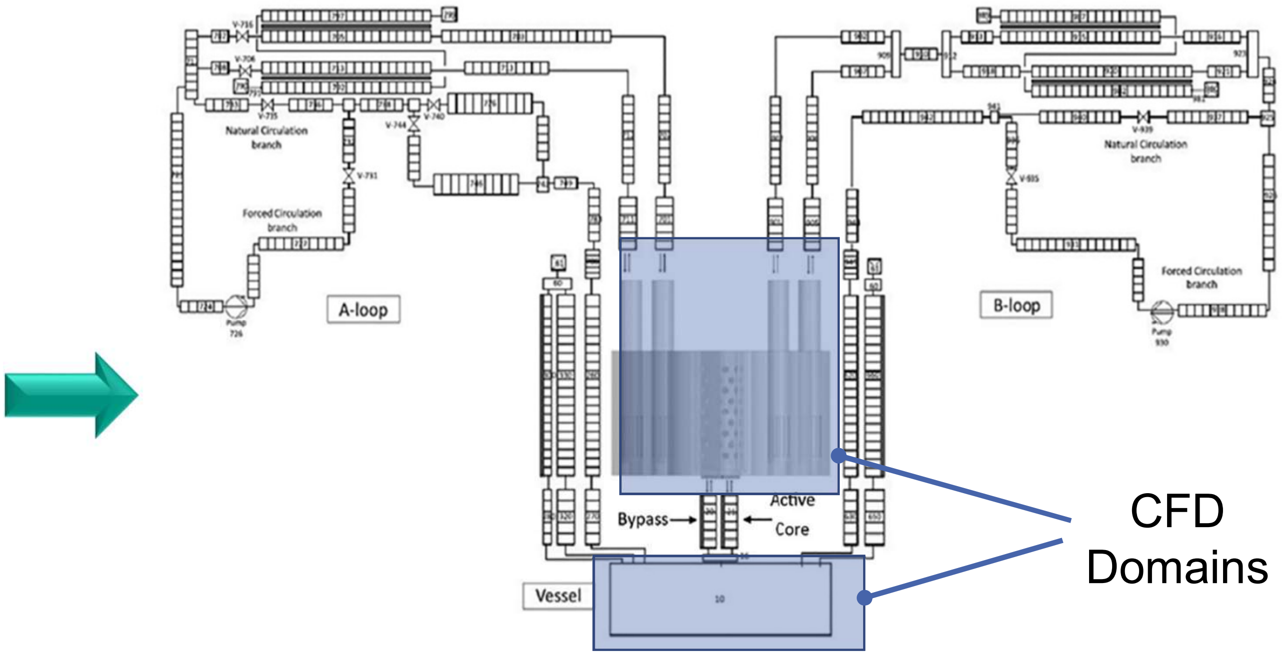
Example : E-SCAPE (European – Scaled Pool Experiment)

- Translation real world

➡ coupled STH + CFD



Van Tichelen, 2015



Toti, 2018

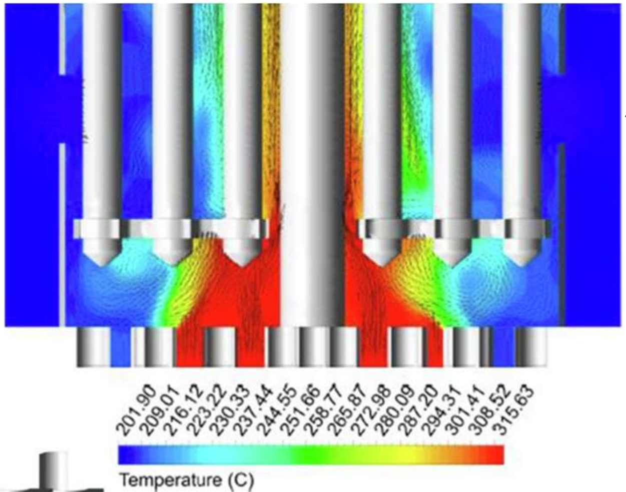
- **Reduction of required meshs from $\mathrm{min.}\ 10^8$ ➡ 10^6**
- **capability to run transient („high fidelity“) but at least trustworthy simulations**

Applications- Pool – coupled STH –CFD

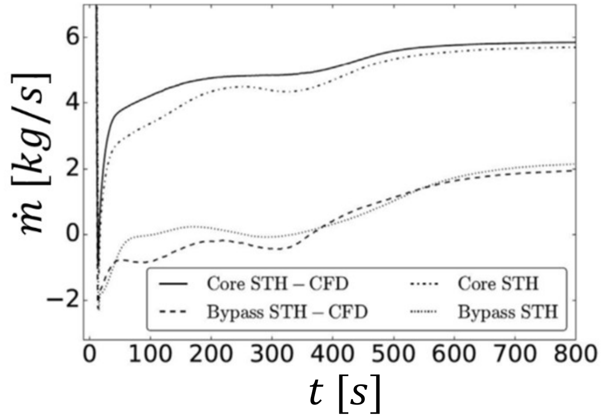
Karlsruhe Institute of Technology

Result for E-SCAPE-Identification of

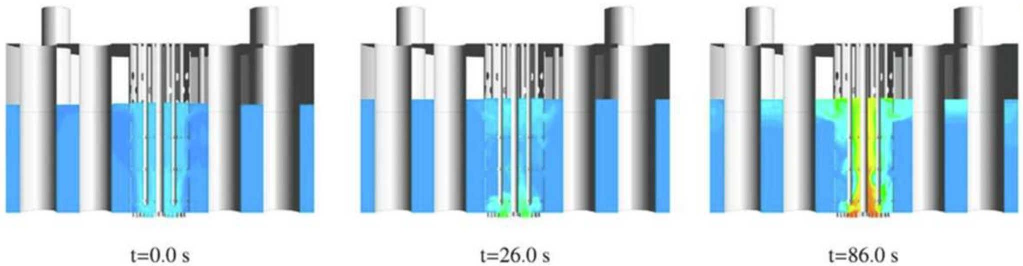
- local design hot spots by flow pattern analysis
- critical time thresholds (flow reversals) during a transient
- ➡ design optimization
- ➡ improved intrumentation



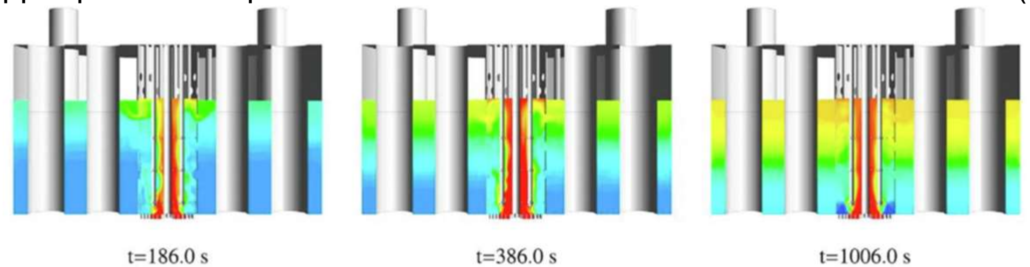
Above core structure temperature distribution 300s after LOFA



Mass flow rate in active and bypass region of core simulator during a LOFA transient



Upper plenum temperature field evolution for a selected vertical section (LOFA)



- Many other examples (e.g. for facilities as TALL, NACIE - LBE , Phenix, EBR-II sodium real reactors) (see Tarantino,2020)

NOTE:

- **identification of all phenomena still indespensibale**
- **many coupled phenomena are still lacking of benchmarks need to be defined**

Synopsis

- Significant progress has been achieved worldwide in understanding of LM thermalhydraulic phenomena due to
  - modelling improvements (AHFM, RSM, numerical schemes, coupling procedures)
  - enhanced collaborations (R&D Centers with Universities, within Europe – EU programs, worldwide through OECD, IAEA)
  - synergetic cross-fertilizing actions of SFR and LFR(ADS) communities
  - increasing computational power
  - advanced instrumentation
- CFD –Thermal hydraulics
  - advanced understanding of complex steady state problems with high degree of confidence (forced convective, mixed convective and buoyant flows-partially) in range of 10-15%
  - significant gaps still existing in flow separation, onset of transitions (bifurcations), free –surface flows confidence level sometimes exceeding 25%
  - Intelligent single effects as well as intelligent integral effects benchmarks (numerical, experimental and both) need to be expanded. CFD guidelines have been elaborated ➡ **establishment of benchmarks mandatory**
- Coupled STH-CFD
  - getting more and more a reference for transient analysis.
  - validation require benchmark library for a set of scenarios (best: in-pile, but also out-of-pile) preferrably with high instrumentation degree ➡ **need for establishment of a library and OECD group**

Literature

- Bandini G. et al., 2015. Assessment of systems codes and their coupling with CFD codes in thermal–hydraulic applications to innovative reactors. Nuclear Engineering & Design, vol. 281, p.p. 22-38
- Grötzbach, G., 2013. Challenges in simulation and modeling of heat transfer in low-Prandtl number fluids. Nuclear Engineering & Design, vol. 264, p.p. 42-55
- Jackson, J. D., 1983, Turbulent mixed convection heat transfer to liquid sodium. Int. J. Heat & Fluid Flow, 107-111.
- Kamide H., Hayashi K., Isozaki T., Nishimura M., 2001. Investigation of Core Thermohydraulics in Fast Reactors – Interwrapper Flow During Natural Circulation. Nucl. Techn., vol. 133, p.p. 77-91
- Kamide H., Ohshima H., Sakai T., Tanaka M., 2015. Progress of Thermal Hydraulic Evaluation Methods and Experimental Studies on a Sodium-cooled Fast Reactor and its Safety. NURETH16, Chicago, USA
- Khafizov, R.R. , Poplavsky, V.M. ;Rachkov, V.I. ; Sorokin, A.P. ; Ashurko, Yu.M., Volkov, A.V., Ivanov, E.F., Privezentsev, V.V., 2015; Experimental investigation of sodium boiling heat exchange in fuel subassembly mockup for perspective fast reactor safety substantiation, Nuclear Energy and Technology, Volume 1, Issue 2, October 2015, Pages 147-152, https://doi.org/10.1016/j.nucet.2016.01.008
- Knebel, J.U., Krebs, L., 1994, Calibration of a Miniature Permanent Magnet Flowmeter Probe and Its Application to Velocity Measurements in Liquid Sodium. Experimental Thermal and Fluid Science 1994; 8:135-148
- Kobayashi J, Takana M., Ohno S., Oshima H., Kamide H., 2015. Proposal of Benchmark Problem of Thermal Striping Phenomena in Planar Triple Parallel Jets Tests for Fundamental Code Validation in Sodium-cooled Fast Reactor Development. NURETH16, Chicago, USA
- Li, R., Chen, X.-N.; Andriolo,L.; Rineiski, A., 2017; 3D numerical study of LBE-cooled fuel assembly in MYRRHA using SIMMER-IV code; Annals of Nuclear Energy, Volume 104, June 2017, Pages 42-52, https://doi.org/10.1016/j.anucene.2017.02.009
- Manservisi S., Menghini F., 2015. CFD simulations in heavy liquid metal flows for square lattice bare rod bundle geometries with a four parameter heat transfer turbulence model. Nuclear Engineering and Design, Vol. 295, p.p. 251-260
- Merzari E., Fischer P., Yuan H., Van Tichelen K., Keijers S., De Ridder J., Degroote J., Vierendeels J., Doolaard H., Gopala V., Roelofs F., 2016. Benchmark Exercise for Fluid Flow Simulations in a Liquid Metal Fast Reactor Fuel Assembly. Nuclear Engineering & Design, vol. 298, p.p. 218-228.
- Nieman, M., Fröhlich, J., 2017, Buoyancy Effects on Turbulent Heat Transfer Behind a Backward-Facing Step in Liquid Metal Flow, doi:10.1007/978-3-319-63212-4
- OECD-NEA, 2015, Assessment of CFD Codes for Nuclear Reactor Safety Problems – Revision 2, NEA/CSNI/R(2014)12
- Pacio, J., Daubner, M., Fellmoser, F. ,Wetzel, Th., 2019, Experimental study of the influence of inter-wrapper flow on liquid-metal cooled fuel assemblies, Nuclear Engineering and Design, Volume 352, October 2019, 110145, https://doi.org/10.1016/j.nucengdes.2019.06.007
- Pacio, J. , Daubner, M. ,Fellmoser, Litfin, K.; Wetzel, Th., 2018, Heat transfer experiment in a partially (internally) blocked 19-rod bundle with wire spacers cooled by LBE, Nuclear Engineering and Design, Volume 330, 15 April 2018, Pages 225-240, https://doi.org/10.1016/j.nucengdes.2018.01.034
- Pacio, J., Litfin, K., Wetzel, T., Kennedy, G., Van Tichelen, K., 2017, Thermal-hydraulic Experiments Supporting the MYRRHA Fuel Assembly. IAEA-CN245-283.

Literature

- Pucciarelli, A, Toti, A., Castelliti, D., Belloni, F., Van Tichelen, K., Moscardini, M., Galleni, F., Forgione, N., 2021, Coupled system thermal Hydraulics/CFD models: General guidelines and applications to heavy liquid metals. Annals of Nuclear Energy 153 (2021) 107990, https://doi.org/10.1016/j.anucene.2020.107990
- Raj, M.N, Velusamy, K., Maity , R. K., 2016, Thermal hydraulic investigations on porous blockage in a prototype sodium cooled fast reactor fuel pin bundle, Nuclear Engineering and Design, Volume 303, July 2016, Pages 88-108, https://doi.org/10.1016/j.nucengdes.2016.04.008
- Roelofs F., Shams A., Otic I., Böttcher M., Duponcheel M., Bartosiewicz Y., Lakehal D., Baglietto E., Lardeau S., Cheng X., 2015. Status and perspective of turbulence heat transfer modelling for the industrial application of liquid metal flows. Nuclear Engineering and Design, vol 290, p.p. 99-106.
- Roelofs, F., Uitslag-Doolaard, H., Dovizio, D. et al. 2019 Towards validated prediction with RANS CFD of flow and heat transport in a wire-wrap fuel assembly, Nuclear Engineering and Design Volume 353, November 2019, 110273, https://doi.org/10.1016/j.nucengdes.2019.110273
- Shams A., Roelofs F., Komen E., 2015. High-Fidelity Numerical Simulation of the Flow through an Infinite Wire-Wrapped Fuel Assembly. NURETH16, Chicago, USA.
- Tanaka, M., Nagasawa, K., 2016, Benchamrk analysis of thermal striping phenomena in planar tripple jets test for fundamental validation of of fluid structure interaction code for SFR, NURETH-16, Chicago, IL, August 30-September 4, 2015, paper-ID 6650
- Tarantino, M., Roelofs, F., Shams, A., Batta, A., Moreau, V., Di Piazza, I., Gershenfeld, A., Planquart, Ph, 2020, SESAME project: advancements in liquid metal thermal hydraulics experiments and simulations. EPJ Nuclear Sci. Technol. 6, 18 (2020), https://doi.org/10.1051/epjn/2019046
- Tenchine D., 2010. Some Thermal Hydraulic Challenges in Sodium Cooled Fast Reactors. Nuclear Engineering & Design, vol. 240, pp. 1195-1217.
- Toti, A., Vierendeels, J., Belloni, F., 2018aa. Coupled system thermal-hydraulic/CFD analysis of a protected loss of flow transient in the MYRRHA reactor. Ann. Nucl. Energy. 118, 199–211.
- Van Tichelen, K., Mirelli, F., Greco, M., Viviani, G., 2015. E-SCAPE: A scale facility for liquid-metal, pool-type reactor thermal hydraulic investigation. Nucl. Eng. Des. 290, 65–77.
- Velusamy, K., Chellapandi, P., Chetal, S.C., Raj, B., 2010, Overview of pool hydraulic design of Indian prototype fast breeder reactor, *Sadhana* Vol. 35, Part 2, pp. 97–128
- Visser, D.C. Roelofs, F. , Mirelli, F. , Van Tichelen, K. 2020, Validation of CFD analyses against pool experiments ESCAPE, Nuclear Engineering and Design, Volume 369, 1 December 2020, 110864, https://doi.org/10.1016/j.nucengdes.2020.110864
- Yu, Y.Q., Merzari, E., Thomas, J.W., Obabko, A.,Aithal, S.M , 2017, Steady and unsteady calculations on thermal striping phenomena in triple-parallel jet, Nuclear Engineering and Design, Volume 312, February 2017, Pages 429-437, https://doi.org/10.1016/j.nucengdes.2016.06.015
- Zhang,K, 2018, The multiscale thermal-hydraulic simulation for nuclear reactors: A classification of the coupling approaches and a review of the coupled codes. International Journal of Energy Research, 2’2’: 44:3295-3315. DOI: 10.1002/er5111