"Liquid metals thermalhydraulics: specific challenges, numerical approaches and experiments"

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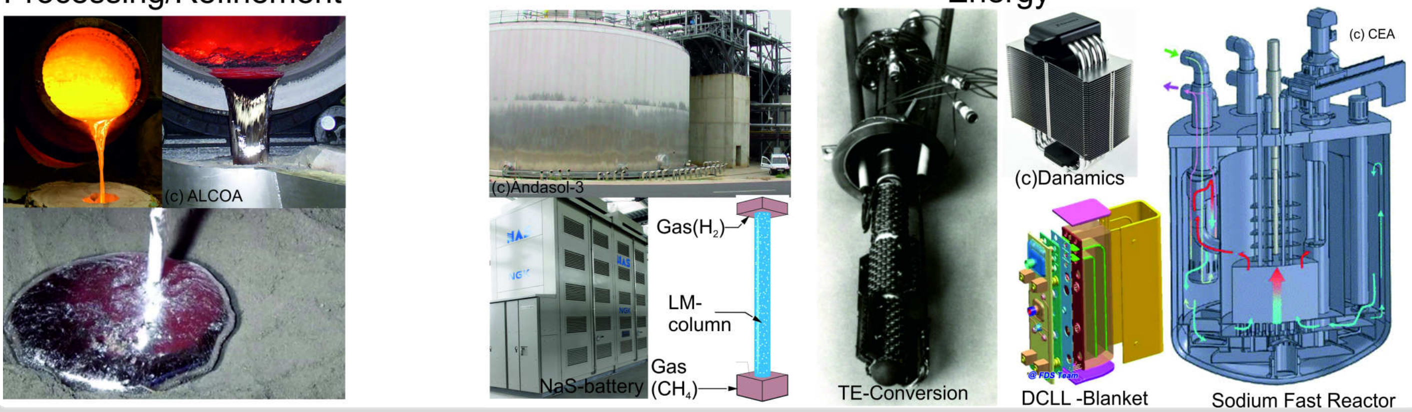
Helmholtz-LIMTECH ALLIANCE

Processing/Refinement

Energy



Content

- **What** alters liquid metals from continuum, where do they appear **?**
- **Fundamentals of liquid metal thermal-hydraulics (TH)**
  - Momentum
  - Energy
- **Core**
- **Pool**
- **System**
- **A glance at free surfaces**
- **How to measure** in liquid metals ?
  - problem of scalars,vectors associated with opaqueness
- **Summary**

Technical Liquid Metal flows

History

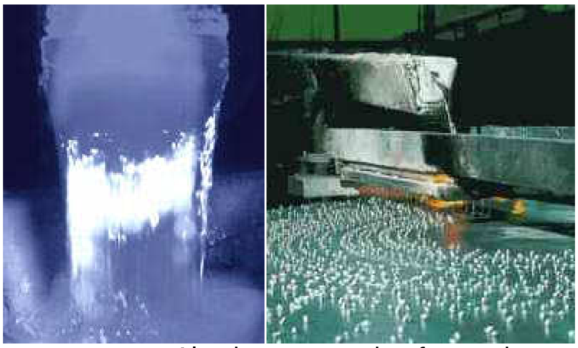
- Liquid metals are known to mankind since about 6000 years (natural Mercury)
- Refinement & casting since more than 4000 years (bronze, copper)
- Iron production in Turkey since 3000 years
- Alumina and Al alloy production on large scales in the last 200years
- Human progress without liquid metals not imaginable

➡ **About 5% of electricity consumption in Europe by Al-production***

Liquid mercury in glass capsule

Bronze casting

Raw iron refinement



Alumina preparation for casting

Industrial interest:

- Adaptive materials
- Minimization of primary energy input
- High demand on quality of surfaces

Requirements:

- Measurement techniques
- Transport phenomena
- Free surfaces
- Active components (engineering)
- phase change problems

* www.world-aluminum.org

Thermal storage in CSP -Plants

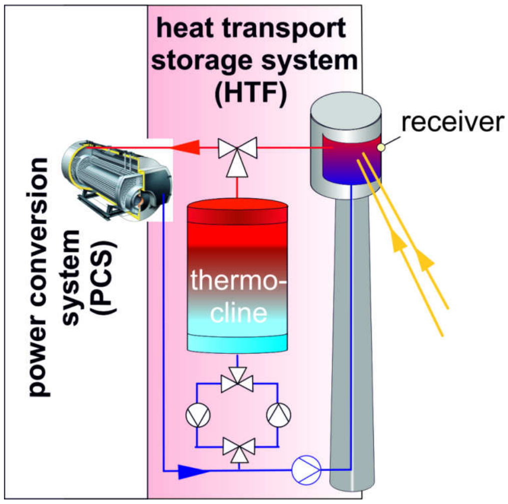
Motivation for liquid metals

- higher temperatures ➡ higher efficiency
- high conductivty ➡ high power density
- excellent heat transfer ➡ fast system response
- low pressure ➡ simple civil engineering

➡ Compact systems

Alkali metals

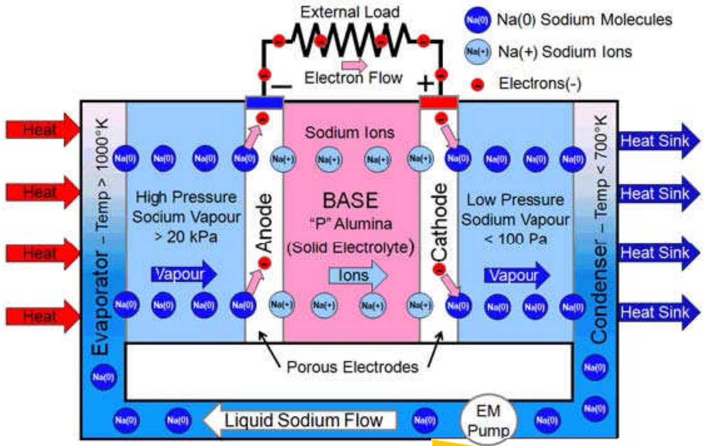
- direct thermo-elec. conversion ➡ efficiency gain



Fluid	Thermal oil at 300°C	Solar salt at 550°C	Air at 600°C, 1 bar	Na (600°C)	PbBi (600°C)	Sn (600°C)
T_{min} [°C]	12	228	-195	98	125	232
T_{max} [°C]	450	560	n.n.	883	1533	2687
ρ [kg/m^3]	812	1903	0,39	808	9660	6330
η [$mPa*s$]	0,22	1,33	0,03	0,21	1,08	1,01
c_p [$kJ/(kg\ K)$]	2,30	1,50	1,12	1,23	0,15	0,24
λ [$W/(m\ K)$]	0,11	0,52	0,06	63,0	12,8	33,8

R. Stieglitz et al.

Thermo- electric conversion



Principle

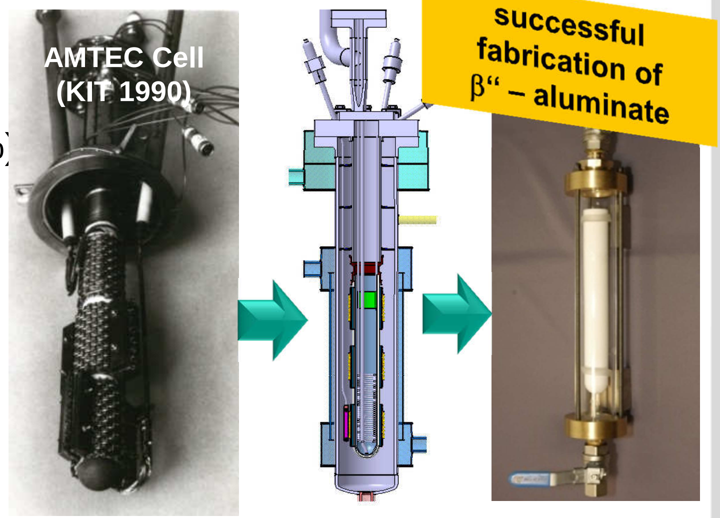
- β''-Alumina solid electrolyte
- Key process: Na-ionization
  (Δp across electrolyte)

Na ➡ $Na^+ + e^-$

- Anode: p~1-2bar; T~600-1000°C
- Cathode: p < 100 Pa; T~200-500 °C

AMTEC perspective

- topping cycle of CSP Plant (η_{AMTEC}>30%)
- return heat sufficient for power plant operation (PCS and/or storage)



H_2 production by thermal cracking of CH_4

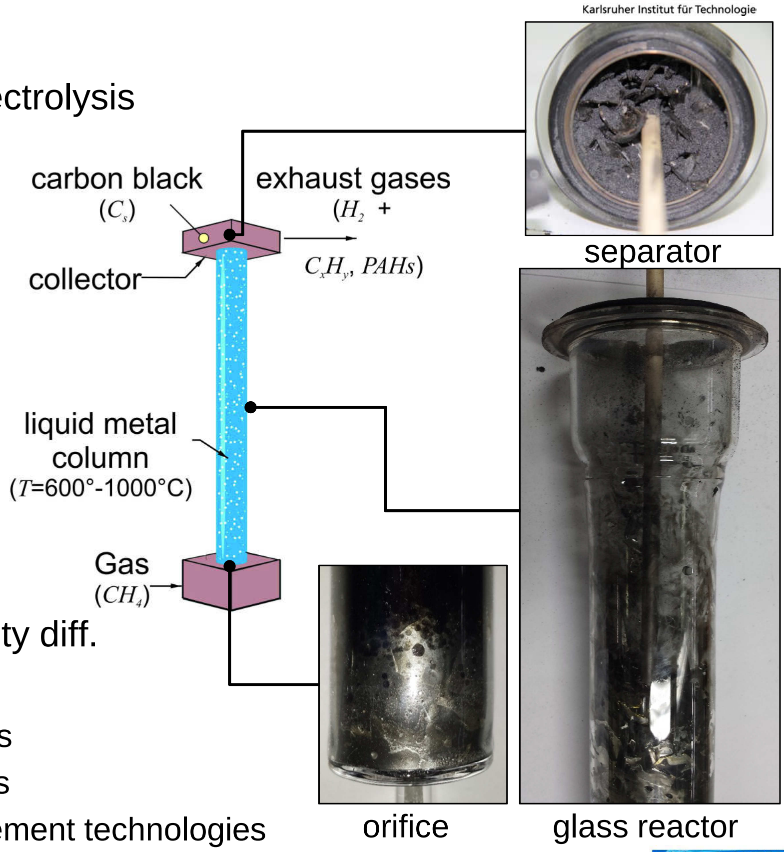
Motivation

- large electricity consumption of electrolysis @ fairly low efficiencies

Idea

- enlarged reaction rates by high contact areas

$$CH_4 \leftrightarrow C + 2H_2 \quad +74{,}85 kJ/mol$$



Achievements &challenges

- ✓ CH_4 cracking success using Sn
- ✓ separation of C functional by density diff.
- efficiency to be improved
  - optimization of process parameters
  - understanding of bubble dynamics
  - experimental validation ➡measurement technologies

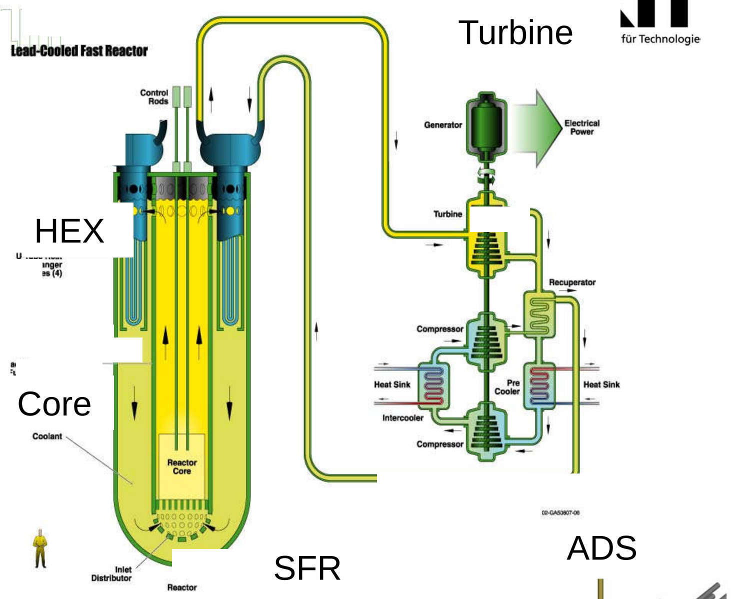
Nuclear Fission: Fast Spectrum Reactors (Na/Pb)

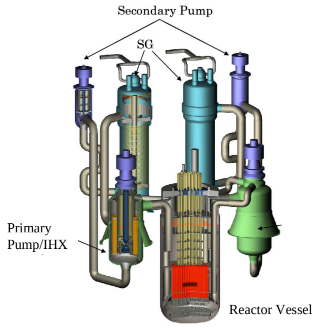
Aim

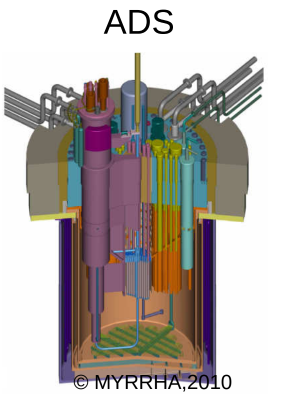
- Potential for transmutation of MA (➨reduction of radiotoxicity
- Better nuclear fuel utilization

Utilization & challenges

- High Temperature applications (electricity, hydrogen prod.)
- Single phase heat transfer in primary system.
- Liquid metal component development & monitoring at high temperatures.



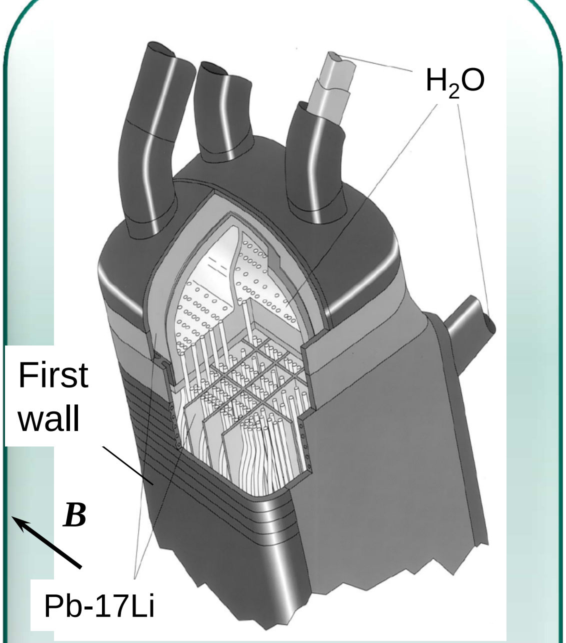




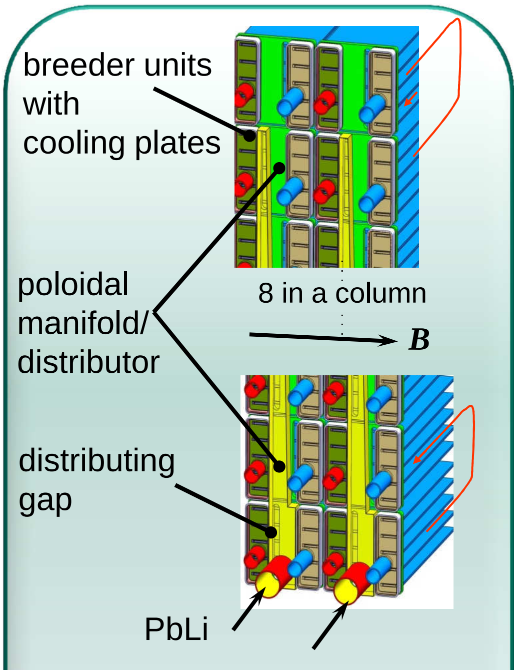
Fusion: Liquid metal blankets

Blanket functions:

- heat removal
- fuel breeding (by *Li* – *n*-multiplication by *Pb*)
- magnet shielding



a) Water cooled blanket - WCLL (Giancarli et al. 2000)

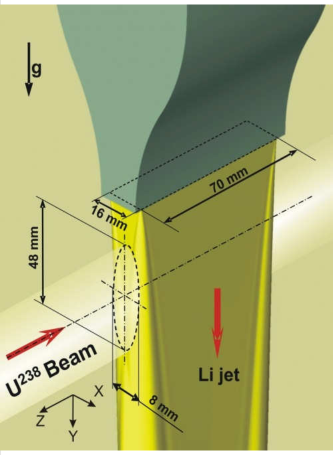


b) Helium cooled blanket HCLL (Giancarli et al. 2000)

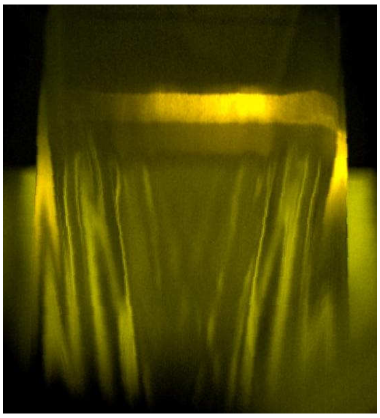
Nuclear Physics: Super-FRS-Target

- Ion accelerator at GSI (U^{238}-Ions, 10^{12} Particles/Spill, 2GeV, Puls duration 50ns) for particle physical experiments for medical applications (www.gsi.de/fair/index.html)
- Solid targets faile since the instantaneous power release: 12 kJ/50 ns ➔ 240 GW
- Generation of a stable Li-Jets in direction of gravity field

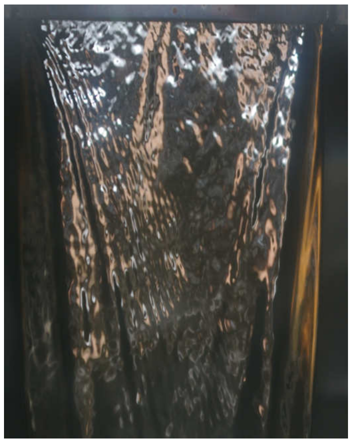
Set-Up



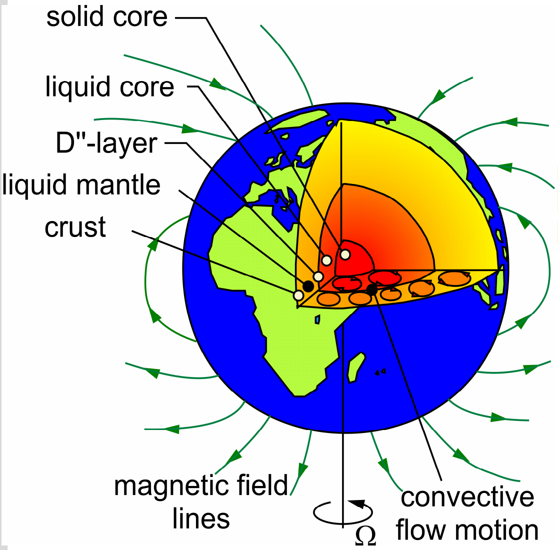
water u_0=2.5m/s



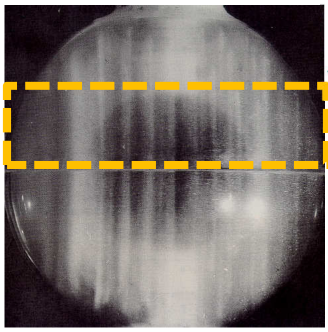
sodium u_0=2.5m/s

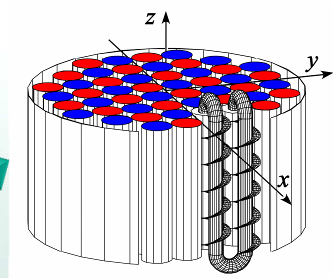


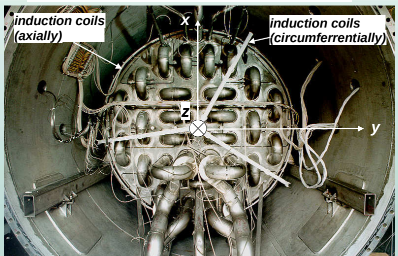
Planetary dynamos

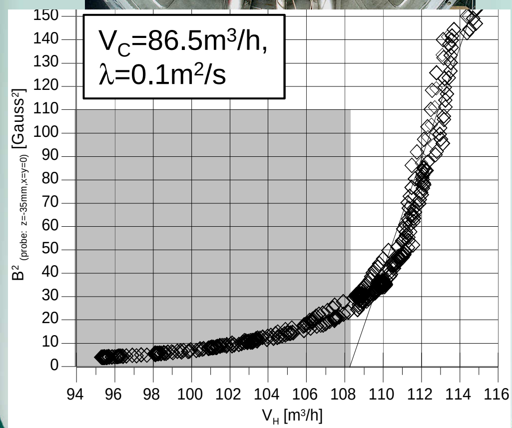


Carrigan ,1985









- exp. proof

Idea

- Coriolis-forces
- Eckman-pumping
- buoyant convection

→ kinemat. dynamo

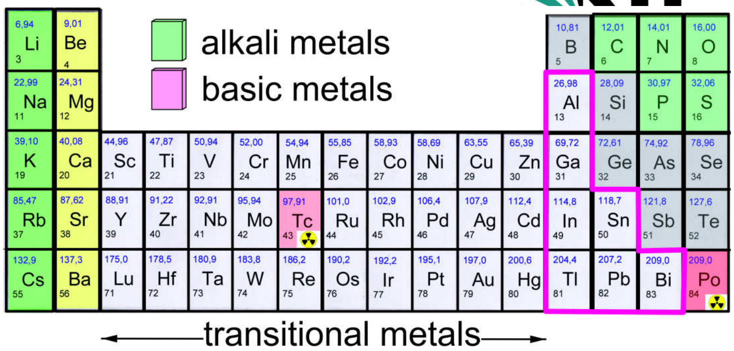
- approximation of flow pattern
- forced convection

* Stieglitz, 2000,2001 ; Phys.Fluids, Science

What distiguishes liquid metals from other liquids ?

Elements suitable for engineering ?

- alkali-metals (Li, Na,K+alloys)
- basic metals (Pb,Ga,Sn+alloys)



	Li	Na	$Na^{78}K^{22}$	Pb	Sn	$Pb^{45}Bi^{55}$	$Ga^{68}In^{20}Sn^{12}$	Hg
T_{melt} [°C]	180	98	-11	327	232	126	11	-39
$T_{boiling}$ [°C]	1317	883	785	1743	2687	1533	2300	356
ρ [kg/m3]*	475	808	750	10324	6330	9660	6440	13534
c_p [J/(kgK)]	416	1250	870	150	240	150	350	140
ν [(m²/s)· 10^{-7}]	7.16	2.6	2.4	1.5	1.6	1.1	3.7	1.1
λ [W/(mK)]	49.7	67.1	28.2	15	33	12.8	16.5	8.3
σ_{el} [A/(Vm)·10^5]	23.5	50	21	7.8	15.9	6.6	8.6	5.7
σ [N/m·10^{-3}] @ T=300°C	421	202	110	442	526	410	460	436

R. Stieglitz et al.

* @ T=600°C, $p=10^5$Pa, except GaInSn, Hg (T=20°C)

Specific properties of liquid metals

- opaque,
- high temperature,
- corrosive,
- high density.
- large surface tension,
- low kinematic viscosity,
- high thermal conductivity,

		Unit	$Pb^{45}Bi^{55}$	Sodium	Water
melting point at 0.1 MPa		[°C]	125	97.7	0
boiling point at 0.1MPa		[°C]	1670	883.1	100
			300°C	300°C	25°C
density	ρ	[kg/m³]	**10325**	880	1000
heat capacity	c_p	[J/(kgK)]	146.33	1304	4180
kinematic viscosity	ν	[m²/s]·10^{-7}	1.754	3.94	9.1
heat conductivity	λ	[W/(m K)]	12.68	**77.1**	0.6
electric conductivity	σ_{el}	[A/(V m)]·10^5	8.428	57	2·10^{-4} (tap)
thermal expansion coefficient	α	/	**6.7.10^{-3}**	2.418.10^{-4}	6·10^{-3}
surface tension	σ	[N/m]·10^{-3}	**410**	**178**	52 (tap)

Specific properties of liquid metals

Physical effects can be expressed force or energy ratios

- Forces : Inertia force $u\frac{\partial u}{\partial x}$, pressure force $\frac{1}{\rho}\frac{\partial p}{\partial x}$, Viscous $\nu\frac{\partial^2 u}{\partial x^2}$, surface tension $\frac{\sigma}{\rho \cdot l^2}$
  buoyancy $g\alpha\Delta T$, Lorentz forces $j\,xB$, gravity g
- Energies : conduction $\frac{\lambda}{\rho}\cdot\frac{\partial^2 T}{\partial x^2}$, convection $c_p \cdot u \cdot \frac{\partial T}{\partial x}$, dissipation $\nu \cdot \left(\frac{\partial u}{\partial y}\right)^2$

Force ratio	$X_{Na(300°C)}/X_{Water(25°C)}$	Energy ratio	$X_{Na(300°C)}/X_{Water(25°C)}$
$Re = \frac{u \cdot l}{\nu}$	2.31	$Pe = \frac{u \cdot l}{\kappa}$	**$2.54 \cdot 10^{-3}$(∇T)**
$Wb = \frac{\rho \cdot u^2 \cdot l}{\sigma}$	0.25	$Ec = \frac{u^2}{c_p \cdot \Delta T}$	3.2
$Gr = \frac{g \cdot \alpha \cdot \Delta T \cdot l^3}{\nu^2}$	**0.21**	$Fo = \frac{l^2}{\kappa \cdot t}$	**$2.54 \cdot 10^{-3}$(t)**
Material ratio			
$Pr = \frac{\nu}{\kappa}$	**$1.1 \cdot 10^{-3}$**	heat conduct. [m^2/s]	128.5

- ***Pr* <<1** ➡ decoupling of viscous scale and thermal scale (Reynolds analogy problem)
- ***Wb*<<1** ➡ scale separation velocity field and surface statistics (high retarding moment), different bubble characteristics
- ***Fo*<<1** ➡ rapid damping of thermal fluctations (spectral impact)

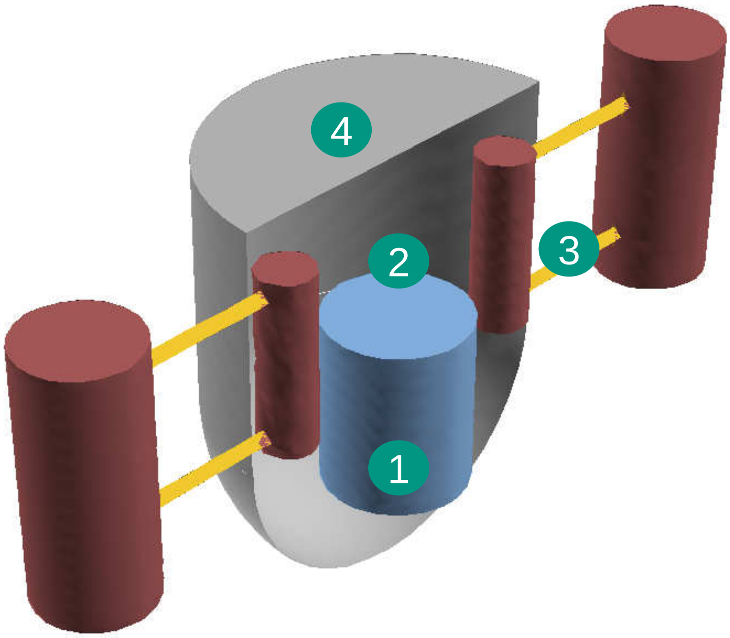
What ?

What distiguishes liquid metals from other liquids ?

General findings ➡ technical impact

- low kinematic **viscosity** ➡ turbulent flow (ν_{H2O}~10-6m²/s)
- high **heat conductivity** ➡ scale separation of thermal from viscous boundary layer (λ_{H2O}~0.6W/(mK))
  ➡ time separation of temperature and velocity fluctuations (different damping !!!!)
- high surface **tension** ➡ different bubble transport/interaction mechanisms
  ➡ scale separation of velocity field and surface statistics (high retarding moment) (σ_{H2O}~52mN/m))
- high elec. conductivity ➡ velocity field modification by strong fields due to ($\vec{v} \times \vec{B}$) (Magnetohydrodynamics)
  ➡ measurement access by electromagnetic means
  ➡ pumping (MHD-Pumps) and/or flow control
- **opaque** ➡ no optical access
- high boiling points ➡ wide operational temperature threshold (ΔT)
- complex **chemistry** ➡ alkali metals with Group V, VI,VII elements
  ➡ exotherm. reactions
  ➡ heavy metals weak reactions with Group V-VII but
  ➡ dissolution transitional metals (structure materials !!!)

Appearance in liquid metal cooled reactors



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- Fundamental liquid metal TH
- Reference data (exp., simulations)
- Model development and validation

1 Core -TH
- Wire wrapped fuel assemblies
- Fuel assemblies with grid spacers
- Sub-channel blockages
- Inter-wrapper flow
- Full core modelling
- Flow Induced Vibrations

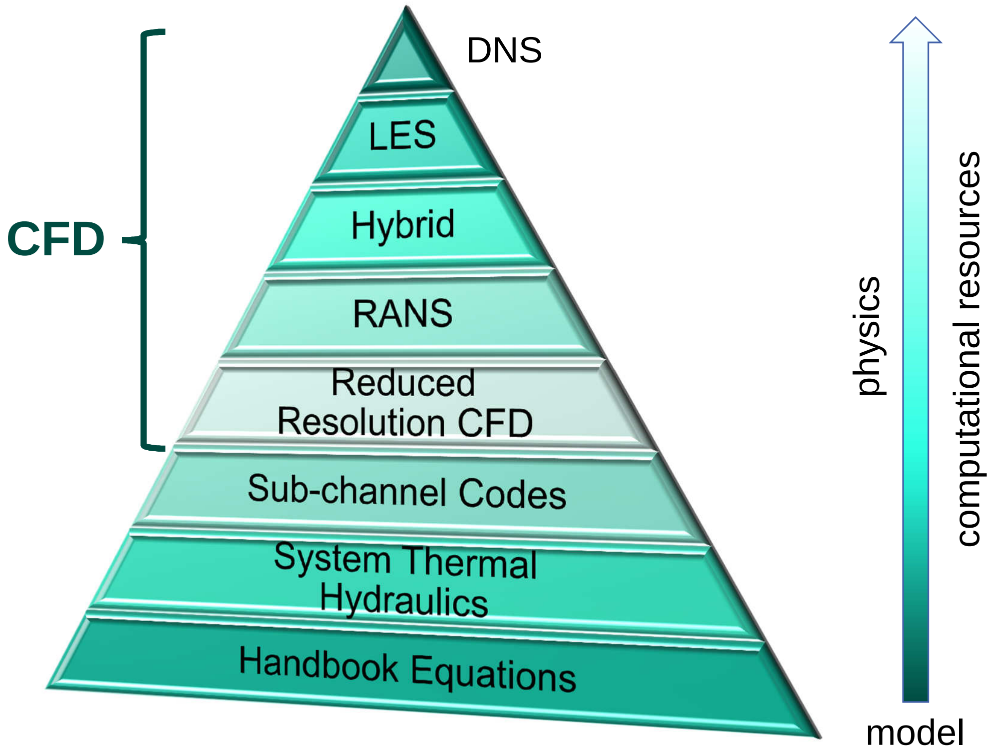
2 Pool-TH
- Model development and validation
- Natural circulation heat removal
- Solidification

3 System TH
- System code development/validation
- Multi-scale model development/validation

4 Free surface TH
- surface shape
- Sloshing (models, droplet formation)

Depicting reality by simulations

- weapons to predict momentum and heat transfer



CAUTION:
- realiable heat transfer prediction requires excellent momentum transfer knowledge

Fundamentals liquid metal TH -Momentum numerics

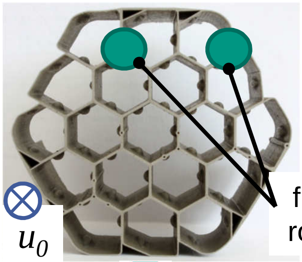
- at a first glance simple- but caution – efforts are considerable

ACTIONS:

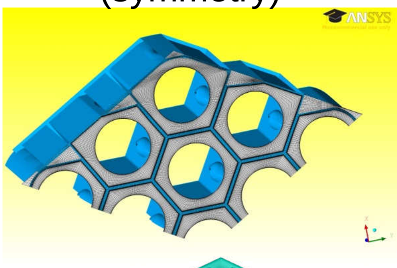
- put numerous cells (fluid, solids) in SA geometry
- provide wall near correction terms for reasonable accuracy (low Re-CFD approach)

Example : Fluid assembly Flow (heated rods)

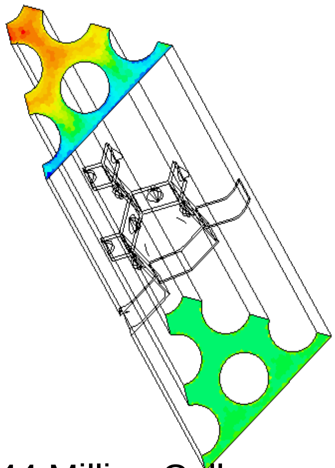
real geometry



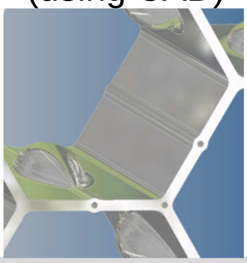
120° fluid mesh (symmetry)



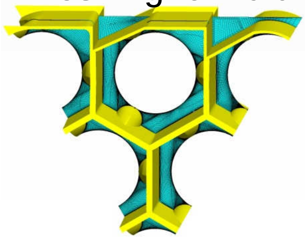
Extrusion to full length (here only 60° shown)



Transfer into solids (using CAD)



Segmented adapted meshing for fluid



44 Million Cells,
6h CPU (Multi-core proc.)
y^+=5 core (≈0.2mm)
boundary layers 0.01mm

Fundamentals liquid metal TH -Momentum numerics

- **Quality of momentum transfer by CFD not only defined by number of cells**

Reynolds averaged modeling (e.g. $u = \bar{u} + u'$) of momentum transport

- Reynolds-Averaged Navier-Stokes (RANS) equations ➡ closure problem in convective term

$$\frac{\partial}{\partial x_i}\left(\overline{u_i}\cdot\overline{u_j} + \overline{u_i^{'}\cdot u_j^{'}}\right)$$

- standard model assumption: gradient hypothesis

$$\overline{u_i^{'}\cdot u_j^{'}} = -\varepsilon_M^{ij}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

- simplification = isotropic exchange coefficient

$$\overline{u_i^{'}\cdot u_j^{'}} = -\varepsilon_M\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

➡ **NOTE:** a real world tensor is transferred to a constant (scalar)

General

- turbulent flow modelling demands **qualified user** (rather than computing power)
- **liquid metals behave like ordinary liquids in bounded (confined) flows**

Fundamentals liquid metal TH -Momentum numerics

- **Momentum transport models based on Re- averaging** $(u = \bar{u} + u')$

standard in codes

in development

Order	isotropic turbulent transport	anisotropic turbulent transport	No. of transport equations
1^{st}	Gradient models, eddy diffusivity models		
	l mixing length models	l_i mixing length models	0
	k-l, k-ε, k-ω, SST, etc.		1,2, ...
	non-linear k-ε, V2-f and branches		2
		ASM models with k-ε	2
2^{nd}	transport equations for all second order closure moments		
		equations for complete shear stress tensor	6+2

Some FACTS

- mixing length models require very qualified user
- turbulence kinetic energy based models as well non-linear models are fragile wrt. to shear flows (wall near flows, jets) but robust for general flow patterns
- ASM models require problem dep. constants for tripple correlations (similars as)
- shear stress models (almost as demanding as DNS)

Fundamentals liquid metal TH -Momentum numerics

What are alternative options for momentum tranfer?

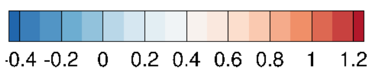
- **Large Eddy Simulation**
  - resolution of the large scales in a DNS manner plus
  - adequate subgrid scale modelling (characterizing viscous dissipation- Vale, Smagorinsky)

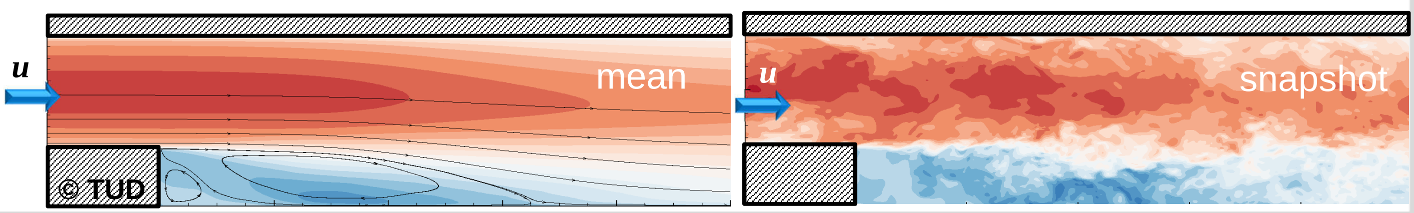
  Challenge (=sources for mistakes)
  - dissipation type for viscous regime (isotropic, non-isotropic)
  - discretisation at high Re (large amount of volumes)
- **Direct Numerical Simulation (DNS)**
  - resolution of all vortices down to smallest scale =quasi-exact

  Challenge (matching simultaneously grid resolution and stability)
  - extreme high number of volumes (computing power)
  - limitation to simple geometries (allowing for use fast solvers) and
  - small mesh Reynolds number (limiting max. flow velocity)

Example: DNS of backward facing step (BFS) Re=4.800

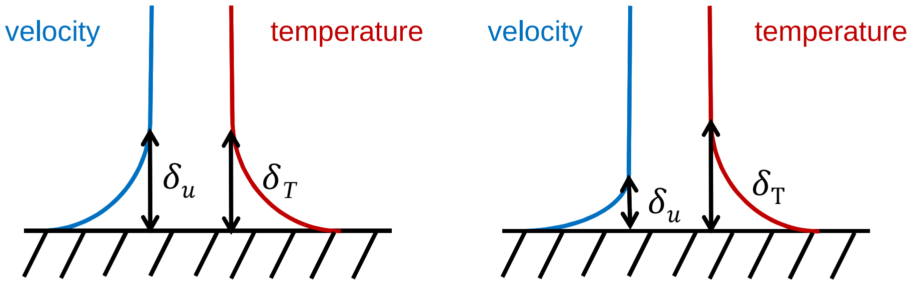
u/u_0





Niemann, Fröhlich et al. 2018, IJHMT

Fundamentals liquid metal TH -Energy



air (Pr ~ 0.71) liquid metal (Pr << 1)

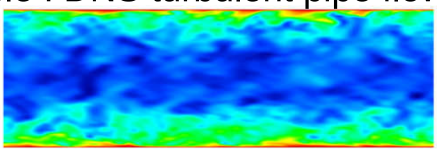
Laminar flow

- momentum boundary layer $\frac{\delta_u}{L} \sim \frac{1}{\sqrt{Re}}$
- thermal boundary layer $\frac{\delta_T}{L} \sim \frac{1}{\sqrt{RePr}}$
- ratio $\frac{\delta_T}{\delta_u} \sim \frac{1}{\sqrt{Pr}}$
- **Reynolds analogy** $\boldsymbol{\delta_T = \delta_u}$

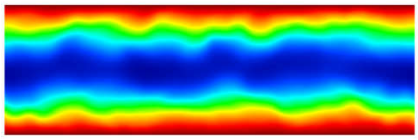
scale separation of thermal and viscous boundary layer !!!

Reynolds –analogy not met !!!

Example : DNS turbulent pipe flow (Re=10^4)



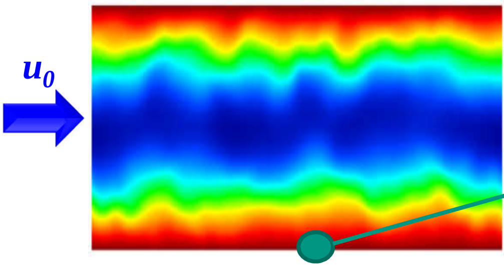
air (Pr ~ 0.71)

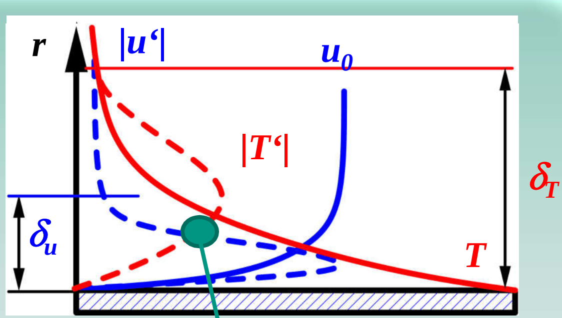


liquid metal (Pr << 1)

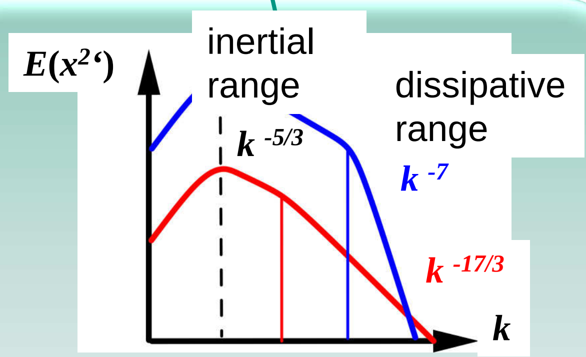
Fundamentals liquid metal TH -Energy

- What about statistical quantities ?





- spatial statistics $r(T_{max}') \neq r(u_{max}')$



- different transport characteristics

Observation

- position of max r (T') ≠ max r (u')
- temperature energy spectra damped and shifted to lower wave numbers k

➡ turbulent heat transport necessitates dedicated turbulence modelling for
  - heat transport and
  - dissipation

Potential solutions

- Reynolds analogy use (best guess, but deficits in mixed convective flows
- Academic models
  - complex, instable
  - not available in commercial codes

Fundamentals liquid metal TH -Energy

Applying Reynolds-averaging (e.g.$u=\bar{u}+u', T=\bar{T}+T'$)

➡ **turbulent energy equation**

$$\rho c_p\left(\bar{u}\frac{\partial \bar{T}}{\partial x}+\bar{v}\frac{\partial \bar{T}}{\partial y}\right)=-\frac{\partial}{\partial y}\left(-\lambda\frac{\partial \bar{T}}{\partial y}+\rho c_p\overline{v'T'}\right),$$

- analogous to turbulent viscosity $\varepsilon_M=\mu_t/\rho$ a turbulent heat flux appears
- ➡ turbulent eddy heat diffusivity $\varepsilon_H=\lambda_t/(\rho\, c_p)$
- ➡ turbulent Prandt number Pr_t

$$Pr_t=\frac{\varepsilon_M}{\varepsilon_H}=f\left(Re, Pr, {}^{y}\!/\!_{R}\right)=\frac{\overline{u'v'}\;\frac{\partial T}{\partial y}}{\overline{v'T'}\;\frac{\partial u}{\partial y}}$$

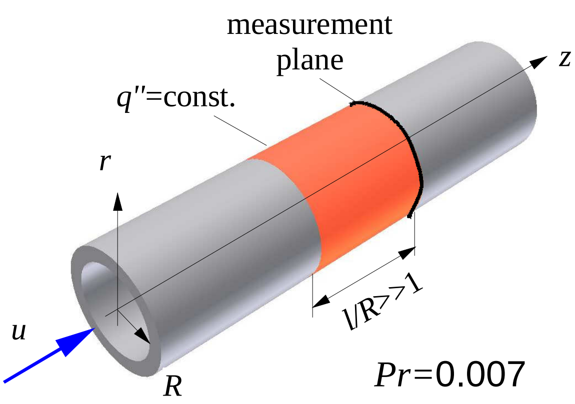
Consequences for Pr_t

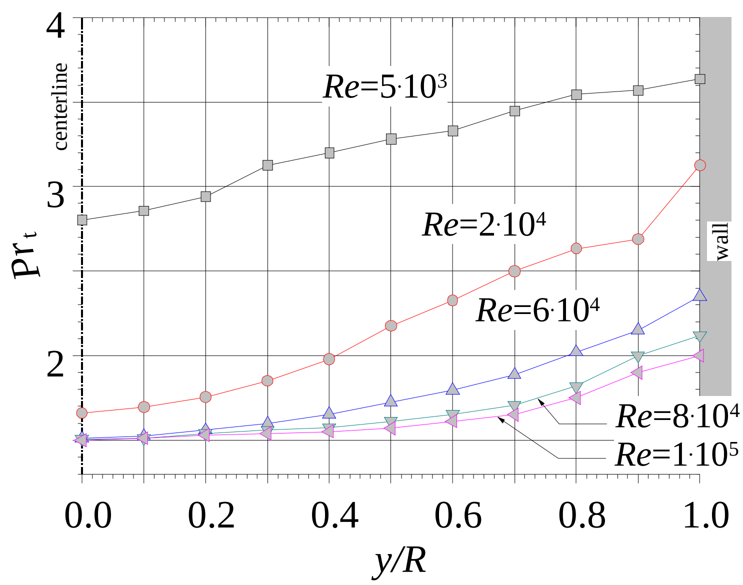
- $Pr_t \neq$ constant (in reality a tensor)
- difficult to measure directly because of dimensions, available sensor size, required temporal resolution and all to be acquired simultaneously
- involves several modelling problems
- hydraulic diameter concept is not valid (except for forced convection)-scale sep.

Fundamentals liquid metal TH -Energy

Is local dependence of Pr_t proofed ?

- Yes, Fuchs (1974) measured in fully (thermal + viscous) developed flow local Pr_t.





Result:

- Local turbulent Prandtl number $Pr_t = f\,(Re,\, y/R)$

CAUTION

- aside from Fuchs in most experiments buoyancy play a considerable role.
- **fully developed flow is either in experiments and computations not given**

Fundamentals liquid metal TH -Energy

How to solve the closure problem of the turbulent heat flux?

- standard approximation: Gradient hypothesis

$$\overline{u_i' T'} = -\varepsilon_H^i \frac{\partial T}{\partial x_i} \quad \rightarrow \quad \overline{u_i' T'} = -\varepsilon_H \frac{\partial T}{\partial x_i}$$

enforced isotropic exchange coefficient ε_H

- **Reynolds – Analogy (Standard in all CFD-Codes)**

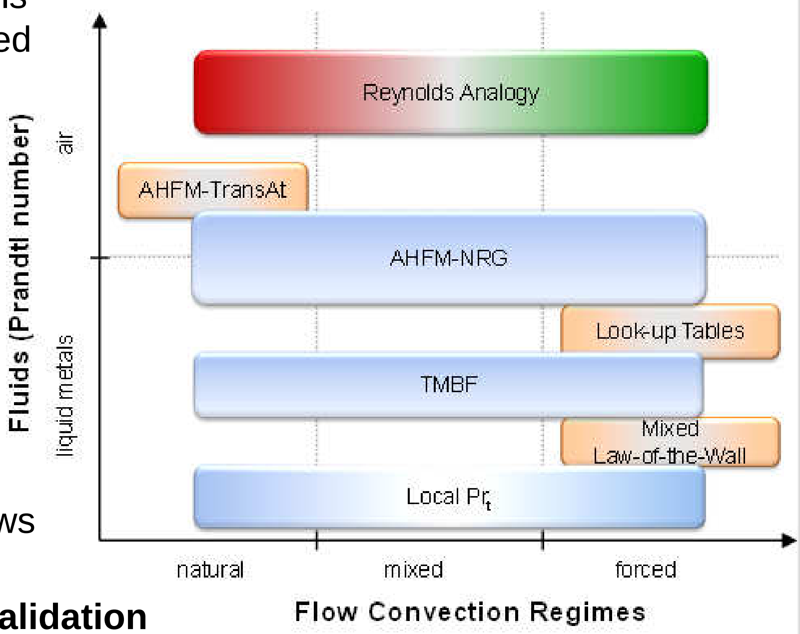
$$\overline{u_i' T'} = -\varepsilon_H^i \frac{\partial T}{\partial x_i} \approx -\frac{\varepsilon_M}{Pr_t} \frac{\partial T}{\partial x_i} \quad \text{with} \quad Pr_t = \frac{\varepsilon_M}{\varepsilon_H}$$

tensor — constant

- **Consequences & typical problems (CFD Simulation with standard Pr_t =0.9)**
  - ***u* and *T*- Statistics completely different, Pr_t is function of Pr_t =(*y*, *Re*, *Pr*, *Gr*)**
  - **no anisotropic diffusivity**
  - **missing transport characteristics (diffusor, recirculation flows, free jets)**
  - ➡ zero-dimensional approach is problematic only valid for forced convection (otherwise extremely qualified user required)
  - ➡ **use of more cells and computing will not help only modelling !!!**
  - ➡ **but (hope) through DNS transport quantities can be computed !!!**

Energy transfer: numerical approach

- Turbulence heat flux model development
  Various modelling approaches developed and tested (Roelofs et al., 2015)
  - work-arounds with existing models
  - application of look-up tables based on existing reference data (DNS and experiments)
  - local turbulent *Pr*- number approaches
  - mixed law-of-the-wall approaches
  - Algebraic Heat Flux Models (AHFM, Shams et al., 2014)
  - four equation models (k-ε-k_θ-ε_θ) (Manservisi & Menghini, 2015)
  - turbulence model for buoyant flows (TMBF, Grötzbach, 2013)
- **Drawback: lacking experimental validation data base**



Fundamentals liquid metal TH -Energy

Why such a flea circus has been successful in some cases and in some cases fail ?

- analysis of dim.-less numbers indispensable :
- relevant are: $Re = \frac{u_0 \cdot d}{\nu}$ $Gr = \frac{g \cdot \beta \cdot \Delta T \cdot L^3}{\nu^2}$ ➡ $Ri = \frac{Gr}{Re^2} = \frac{g \cdot \beta \cdot \Delta T}{u_0^2} = \frac{buoyancy}{inertia}$

REASON

- existence of different flow domains

e.g. in forced convective flow Reynolds-analogy applicable for low heating powers

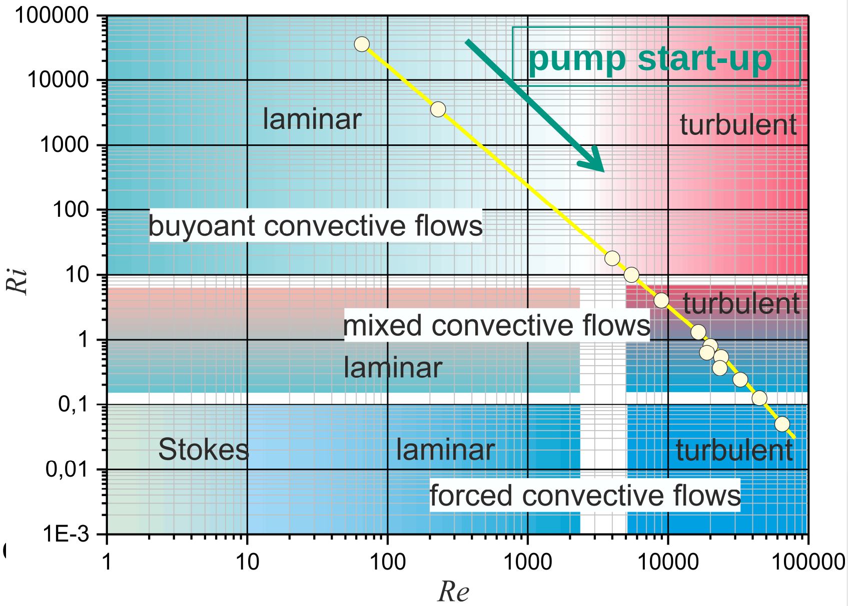
OCURRENCE

- pump start –up/shut down
- Loss Of Flow Accident (LOFA)
- Station Black Out (SBO)

➡ several flow regimes covered

Conclusion:

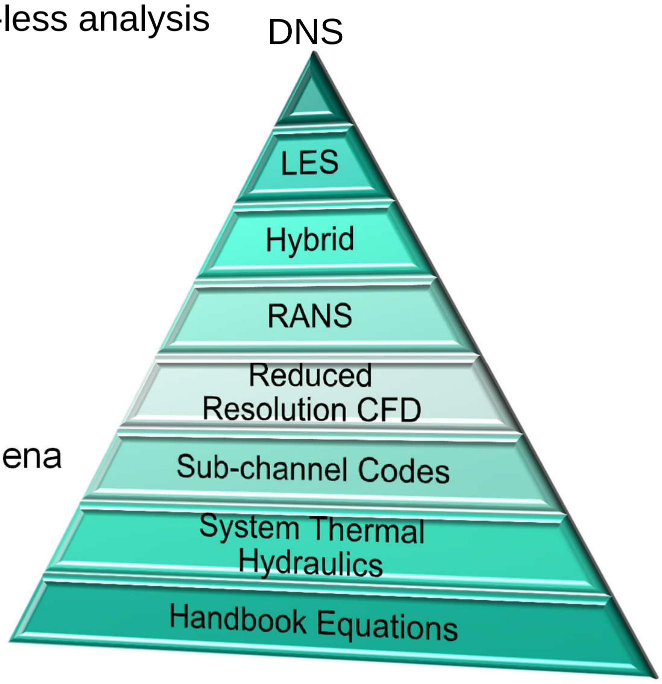
- **a careful analysis of flow regim[e] assessment/simplifcation of comp. tools/models to be used**



(Re-Ri for heated pipe flow)

Summary- liquid metal heat transfer –General

- Analyze first the problem by means of dim.-less analysis
  - identification flow regime to be tackled
- Literature study on similar problems
- Selection of simulation tool considering
  - application
  - purpose
  - required accuracy
  - available man power/budget
  - assessment of computation time
- Modular computation chain
  - first verification of fundamental phenomena
  - validation if possible
- Quantify uncertainties if possible



Through entire simulation chain

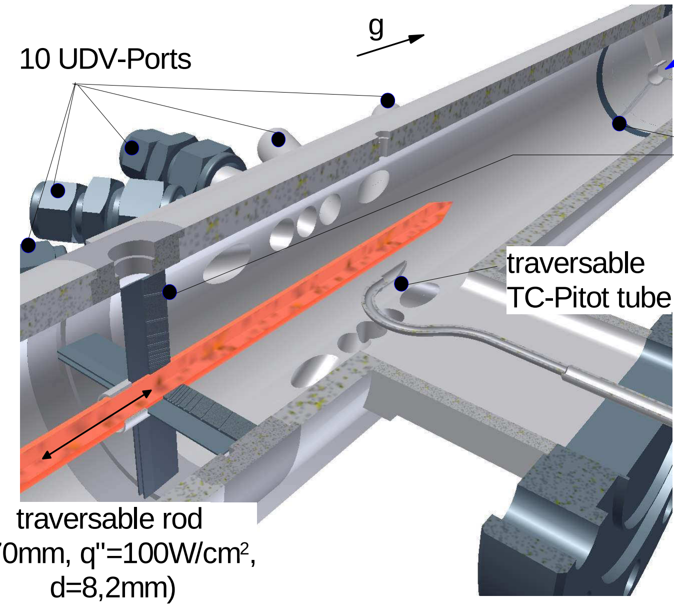
- Use best practice guidelines for CFD
  - generic guidelines available e.g. ERCOFTAC
  - specific liquid metal one under development in the H2020 SESAME project)

Core – Fuel pin flow

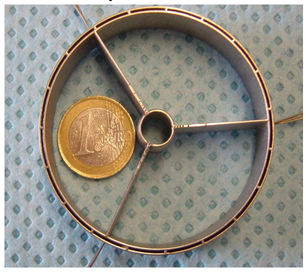
Background : Pin single element of fuel assembly

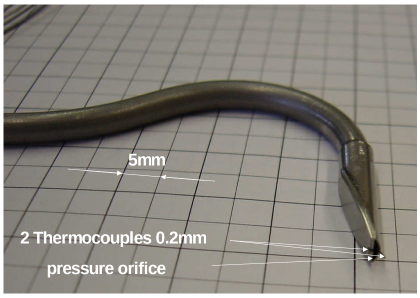
Scope : Turb. heat transfer in forced, mixed and buoyant convective flows ($Re \rightarrow 6 \cdot 10^5$)

Measure:
- Development of models for turbulent heat flux;
- Determination of Nu-correlations;
- Evaluation of transitional regimes (model validity).



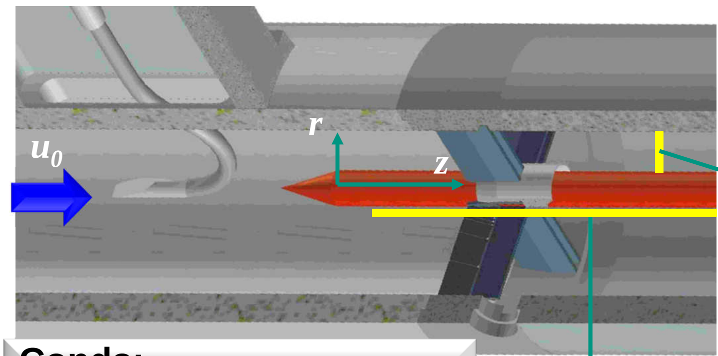
3 Rakes (60 TC´s, d=0.25mm)



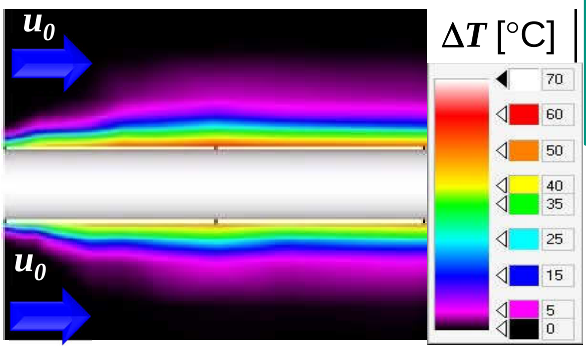


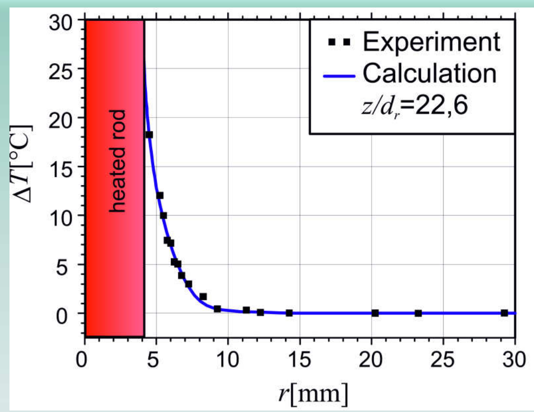
Core – Fuel pin flow

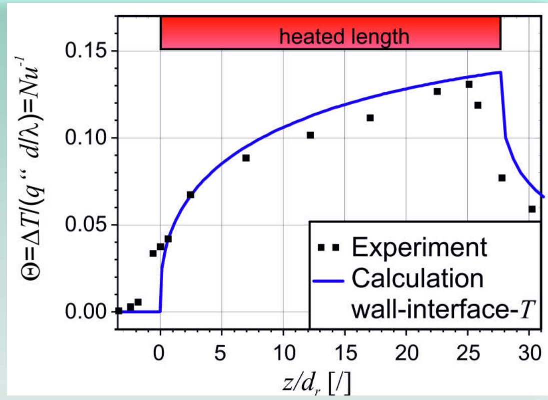
- Observation: -high heat conductivity λ



Conds:
$Re = 3.1 \cdot 10^5$, $q'' = 40$W/cm², PbBi @ T_{in}=300°C

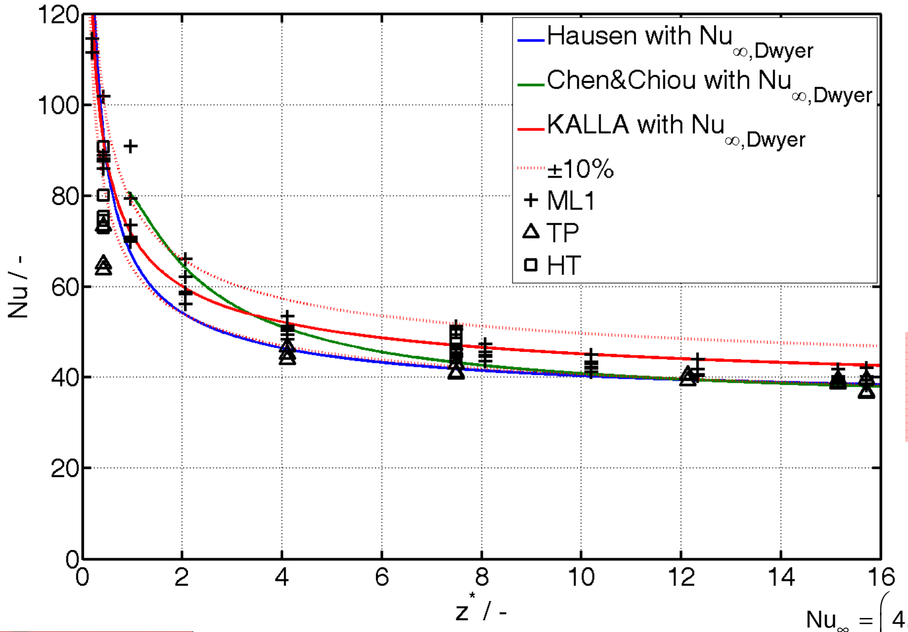






 R. Stieglitz et al. Pr=0.02

Core – Fuel pin flow - developing flow



$$\frac{Nu_{z,Hausen}}{Nu_{\infty}} = 1 + \left(\frac{d_h}{z}\right)^{\frac{2}{3}}$$

$$\frac{Nu_{z,Chen\&Chiou}}{Nu_{\infty}} = 1 + 2.4\frac{d_h}{z} - \left(\frac{d_h}{z}\right)^{2}$$

$$\frac{Nu_{z,KALLA}}{Nu_{\infty}} = 1 + 1.14\left(\frac{d_h}{z}\right)^{\frac{1}{2}}$$

Nu_{∞} according to Dwyer:

$$Nu_{\infty} = \left(4.63 + \frac{0.686}{b}\right) + \left(0.02154 - \frac{0.000043}{b}\right)\cdot\left(\overline{\Psi}\cdot Pe\right)^{n}$$

$$\overline{\Psi} = \left(1 - \frac{1.82}{Pr\left(0.0185\,Re\sqrt{f_{wm}}\right)^{1.4}}\right) = \left(Pr_t\right)^{-1}$$

$$n = 0.752 + \frac{0.01657}{b} - \frac{0.000883}{b^2};\quad b = \frac{d_r}{D}$$

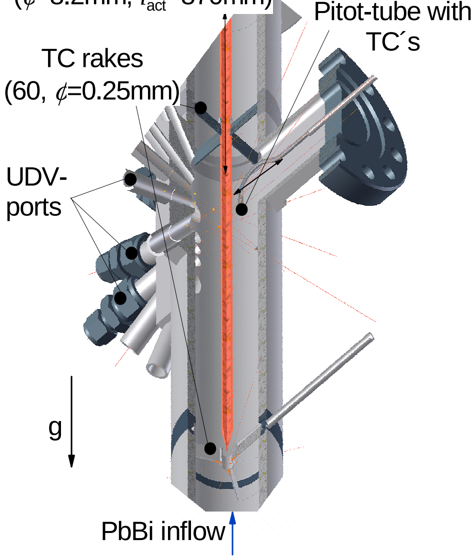
$Pr = 0.02$

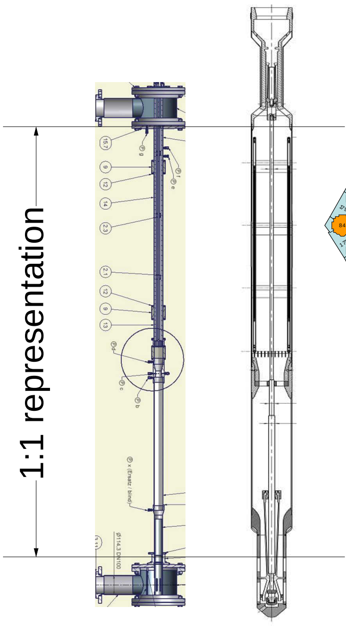
Experimental investigation of the turbulent heavy liquid metal heat transfer in the thermal entry region of a vertical annulus with constant heat flux in the inner surface
L. Marocco, A. Loges, Th. Wetzel , R. Stieglitz, International Journal of Heat and Mass Transfer

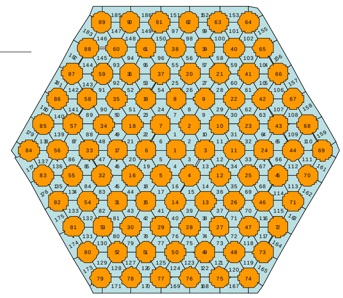
Core – Fuel pin ➡ Fuel Assembly (FA)

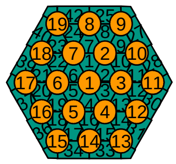
- **Strategy**

Single pin ➡ **Bundle** ➡ **Assembly simulator**





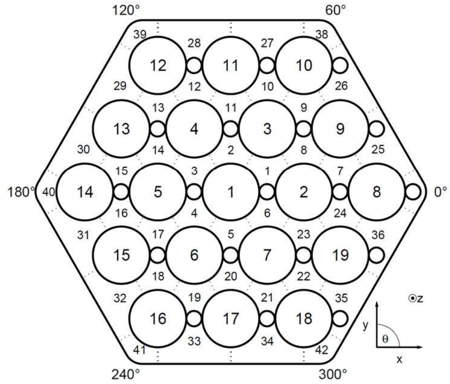


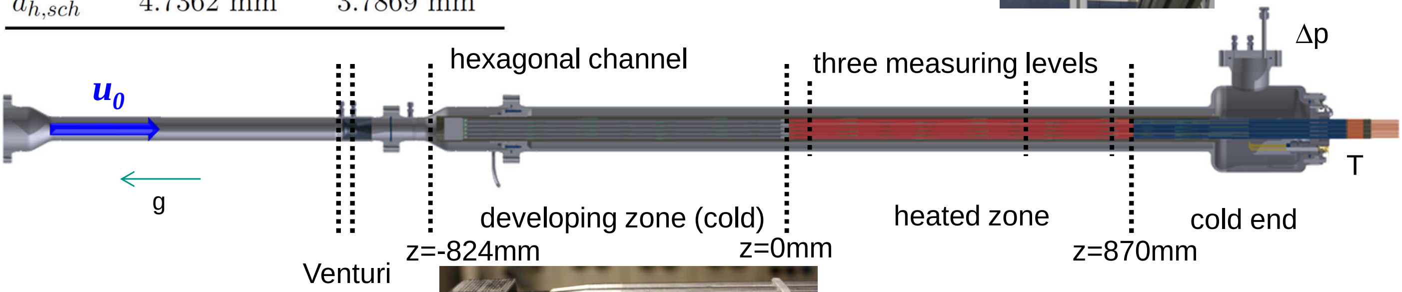


- Complementary CFD simulation ➡ system analysis codes

Core – Fuel Assembly (FA)

Symbol	KALLA test	MYRRHA
N	19	127
D	8.2 mm	6.55 mm
P	10.49 mm	8.38 mm
P/D	1.279	1.279
d	2.2 mm	1.785 mm
H	328 mm	262 mm
L_{heat}	870 mm	600 mm
A_{bdl}	1027.23 mm^2	3656 mm^2
$d_{h,bdl}$	5.2015 mm	4.007 mm
A_{sch}	19.343 mm^2	12.343 mm^2
$d_{h,sch}$	4.7362 mm	3.7869 mm

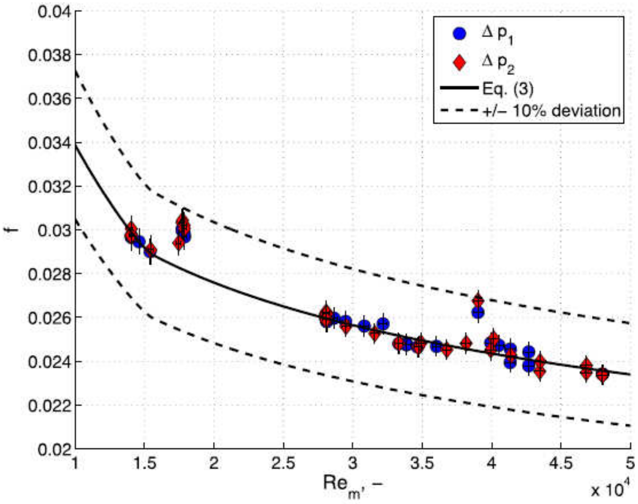




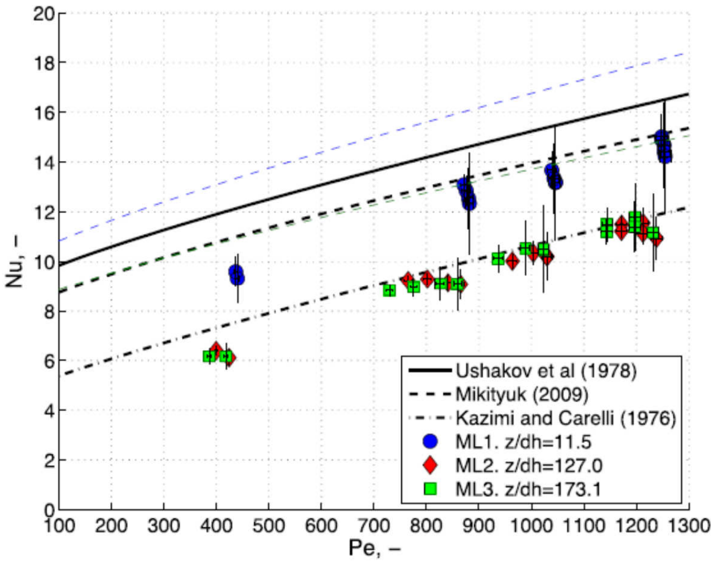
Re = 2.100 – 63.100

Core –Fuel Assembly (FA)

KALLA Experiments (Germany)



Pacio et al. (2016)



pressure drop Δp
- high reproducibility
- low uncertainty
- Correlations of Cheng &Todreas (1986): RMS = 3.8%, all data within 8%

heat transfer (local Nu)
- at 2 flow rates & 3 powers reproducibility
- flow not fully developed at ML1
- @ low Pe: best fit with Kazimi (1976) correlation
- @ high Pe: best fit with Mikityuk (2009)

Which is exact solution ?
What occurs at mixed convection ?

Core – Fuel Assembly (FA)

Drawback of experiments

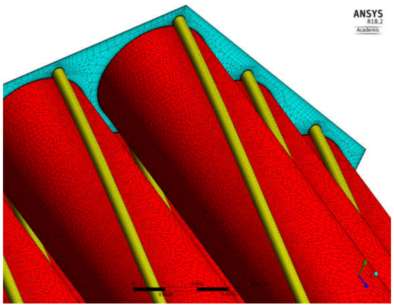
- infos only on scalars (T, Δp) but
- no local data (hot spots)
- transport quantities
- ➡ **CFD is only option for access on local data**

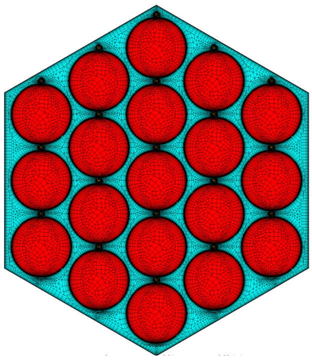
SESAME

Example

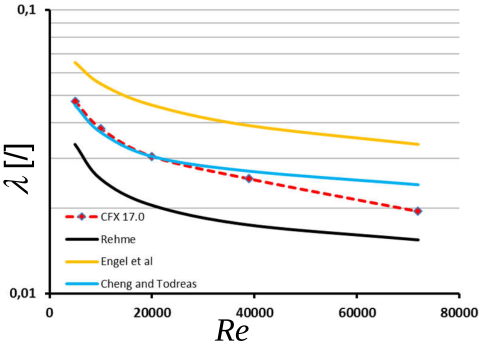
19 Rod Bundle, y^{+}~1 (Δy=5µm)

P/D =1.1, D=9.6mm ➡ 10^8 cells in CFD !!!



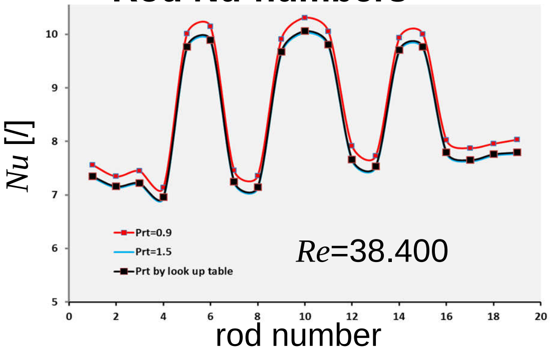


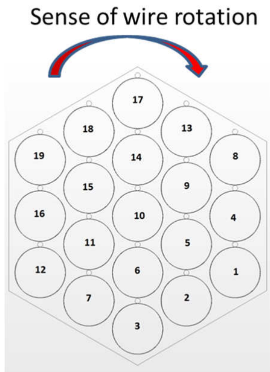
Check scalars !



- friction factor λ ✓

Rod Nu-numbers

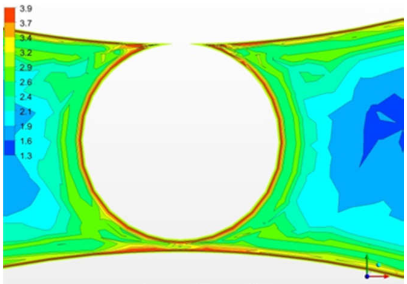




Core – Fuel Assembly (FA)

Close up to local data

- Pr_t between wire wraps change strong

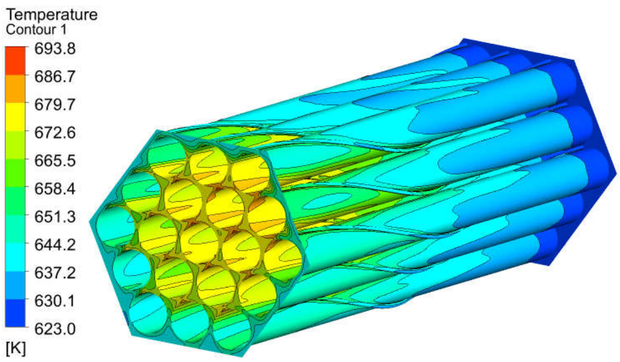


Example

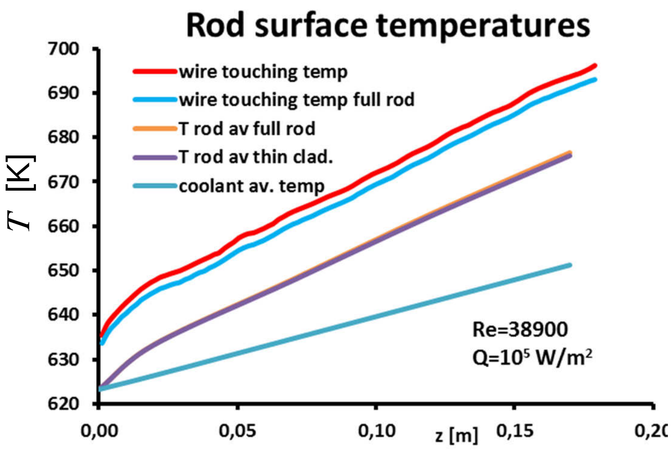
SESAME

19 Rods, y^{+}~1, P/D =1.1, D=9.6mm, Re=38.900

- while fluid ΔT remain modest



- but, structure temperature exhibit large ΔT

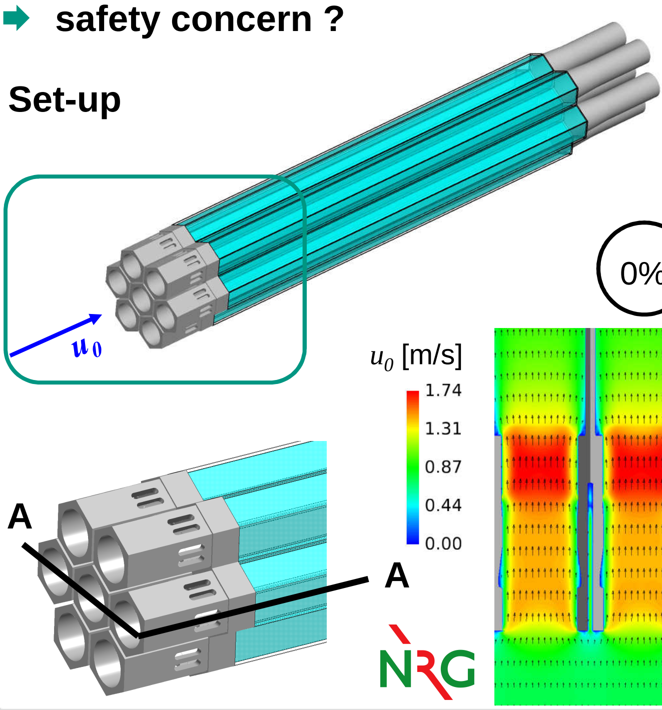


Core- Fuel Assembly (FA) -blockage

SAFETY - local FA blockag in active zone

- small, low thermal conductivity λ_w, no porosity causing reduced flow
- rise of temperature in blocked channel
- ➡ **safety concern ?**

Set-up

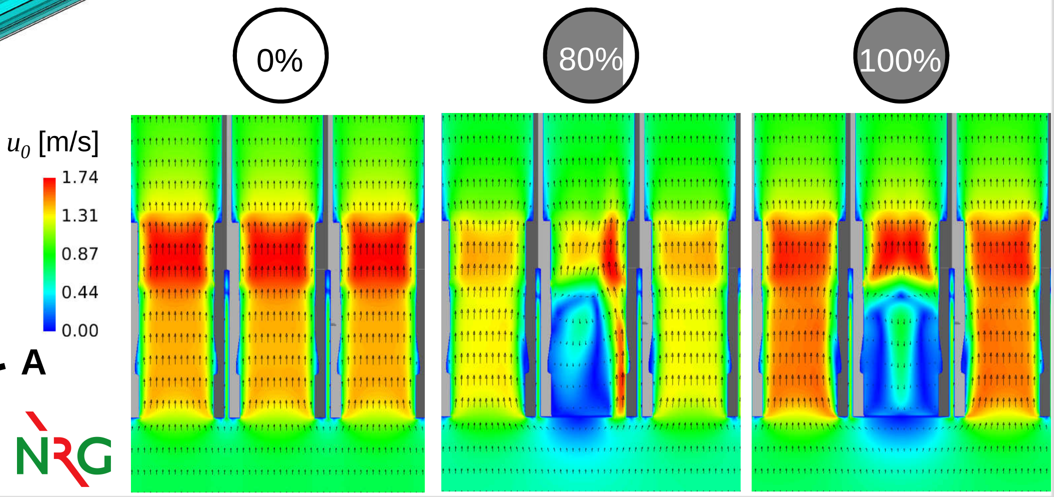


Model assumption

- inlet blockage
- porous medium ansatz for obstacle

Result for cut A-A plane

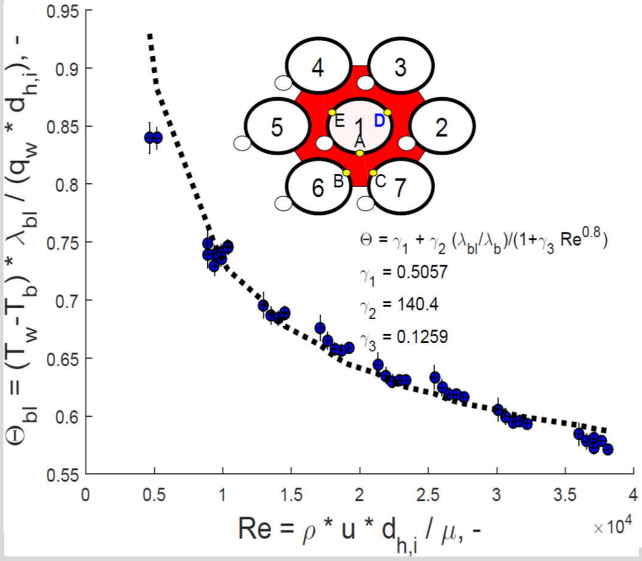
- inlet blockage
- porous medium ansatz for obstacle



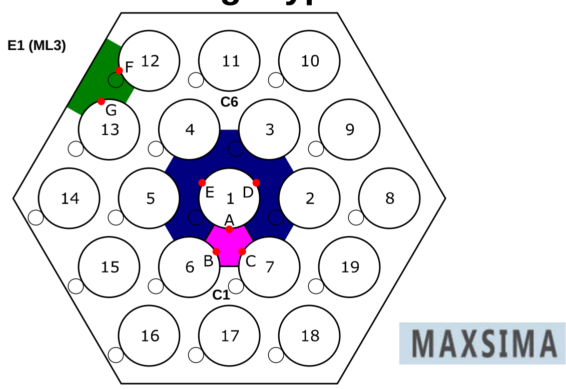
Core- Fuel Assembly (FA) -blockage

Corresponding experimental findings

- additional Δp <2% for all types studied
- ➡ detection within reactor hardly feasible
- ➡ **KBE**: non-dim. **K**arlsruhe **B**lockage **E**quation
  - including effects of (Re) and
  - thermal conductivity λ_w for each blockage type



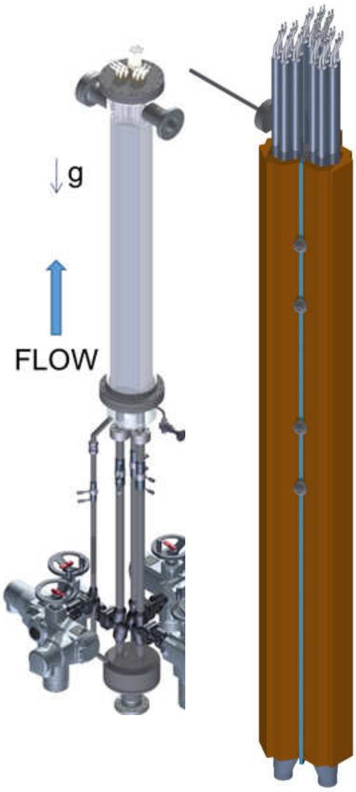
3 blockage types studied



Scenario	$T_w - T_b$, K	Factor
Empirical Nusselt-number correlations		
Kazimi and Carelli (1976)	34.3	1.00
Ushakov et al. (1978)	24.7	0.72
Experiments in unblocked bundle		
Mean wall temperature	34.6	1.01
Maximum wall temperature	67.6	1.97
Experiments with blockages, λ_{bl} = 4 W/Km		
Small central blockage (C1)	100.2	2.92
Small edge blockage (E1)	134.2	3.91
Large central blockage (C6)	673.2	19.63

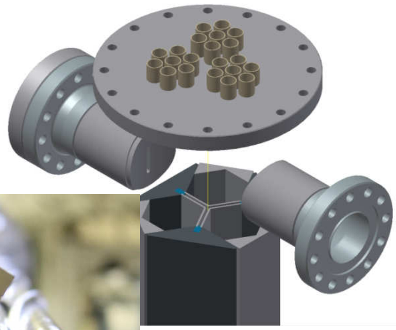
➡ **blockages can lead to ΔT > acceptable T_{pin}**

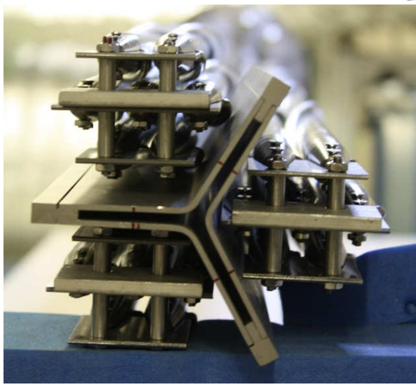
Core- flow between FA- inter wrapper flow (IWF)



Next to be studied

- KALLA Inter Wrapper Flow experiments under design
  - 3 x 7-pin bundles including inter wrapper channels
- numerical support and validation





SESAME

Summary- core thermal hydraulics

Recommendations

- Correlations for Nu, dp need to be carefully checked for your case
- FA flow hydraulics depends strongly on pin spacing measures (spacers or wire-wraps).Quality assurance in terms of V&V
  - by high fidelity numerical reference data complemented by
  - experimental data from real case or literature
  - “healthy” hydraulics is pre-requisite before entering heat transfer simulations

Trends

- Towards non-idealistic geometries taking into account effects
  - pressure fluctuations at inlet
  - operational deformations
  - Fluid structure interactions
- Further development of complete core approaches starting from inter wrapper flow analysis

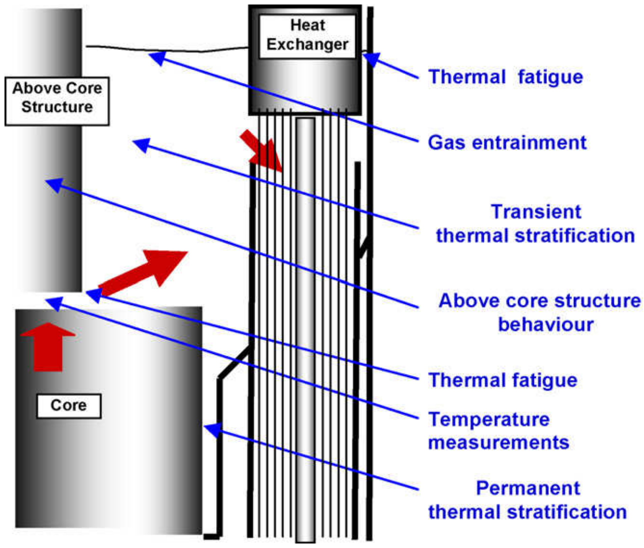
Pool thermal hydraulics (TH) – scope & target

Vital to quantify reactor performance and exploit safety threshold

- **Scientific questions to be answered**
  - **core coolability**
    - heat transfer
    - overcooling (danger of freezing)
    - transient flow behaviour
    - natural circulation (grace times)
  - **structural loads**
    - thermal stratification (low cycle fatige)
    - thermal fluctuations (high cycle fatigue)
    - flow induced vibrations (flow instabilites)
    - coolant level fluctuations (sloshing)
    - cover gas behaviour
  - **gas/vapour/particle transport**
    - gas entrainment (reactivity changes in core)
    - fission product transport (maintenance)

➡ **single effect phenomena**

➡ **scale interaction effect phenomena**



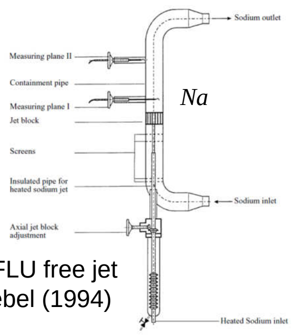
Upper plenum challenges
(© Tenchine, Nucl. Engng. Des, 2010)

More infos in overview papers e.g. from Tenchine (2010), Velusamy et al. (2010), and Roelofs et al. (2013)

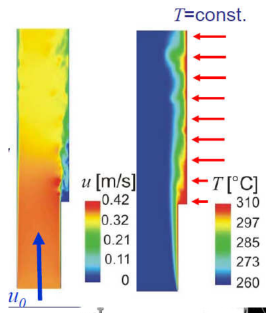
Pool thermal hydraulics (TH) – exp. approach

mainly 3 stage strategy

- single effect (SE) tests
  - conducted in liquid metal
  - high degree of instrumentation
  - costly & time consuming
  - indispensable for V&V

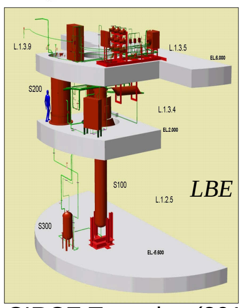


TEFLU free jet
Knebel (1994)

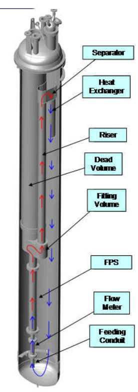


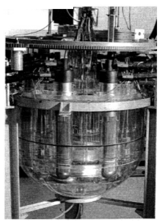
vertical backward facing step-BFS, Niemann et al. (2018)

- Scaled experiments
  - mixed water & liquid metal experiments
  - liquid dependent type of instrumentation
  - calibration of multiphysics – multiscale tools, system codes



CIRCE Tarantino (2011)



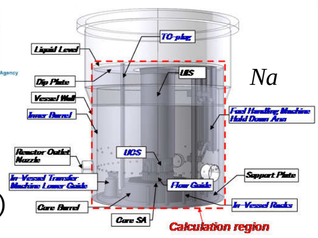


Ramona

H_2O

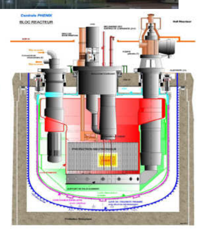
MYRRHABelle, Spaccapaniccia et al. (2015)

- Prototype experiments
  - only with reference liquid metal
  - pre-requisite for licensing



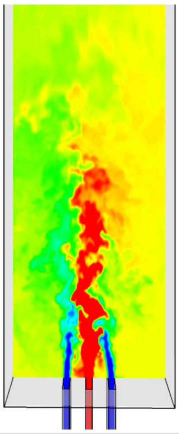
Monju-benchmark Ohira (2013)

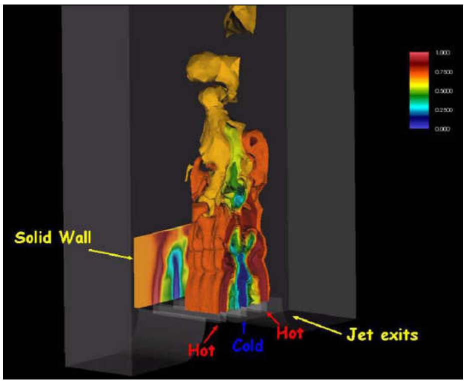
IAEA Phenix benchmark, 2016

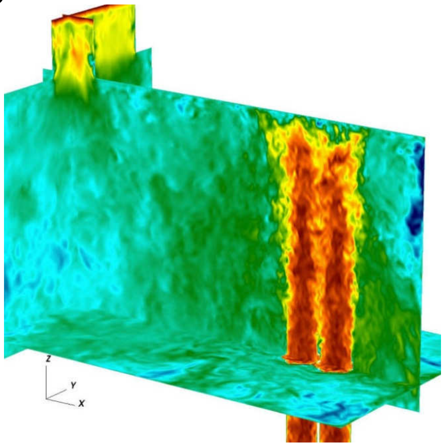


Pool TH – computations single effect (SE)

- Separate effect: Mixing Jets (Roelofs et al., 2013)
  - 'Quasi' DNS approach (Kimura, 2002) and LES/DNS approach (Otic and Class, 2007) for reference
  - LES leads to accurate results (Cao, 2010 & Tenchine, 2013)
  - No dependence on SGS models for LES (Jung and Yoo, 2004)
  - RANS models overpredict temperature fluctuations (Kimura, 2002 & Choi and Kim, 2007)
  - Advanced anisotropic RANS with heat flux model outperform standard RANS models (Nishimura, 2000)
  - Algebraic heat flux models required (Arien, 2004)
  - Sensitivity to Prandtl number (Durve, 2010)
- **still certain degree of V&V uncertainty existent !!!**





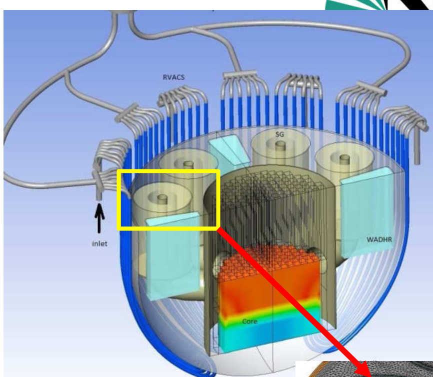


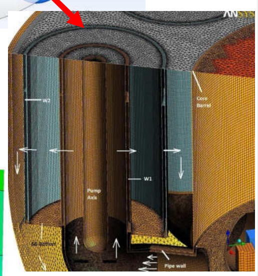
Pool TH– computations on reactor scale

Example: ELSY model (Pb-cooled reactor)

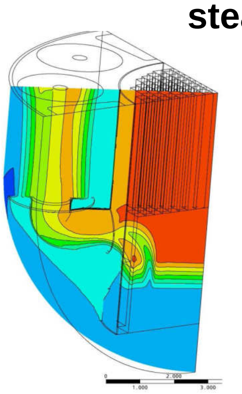
Scientific question:

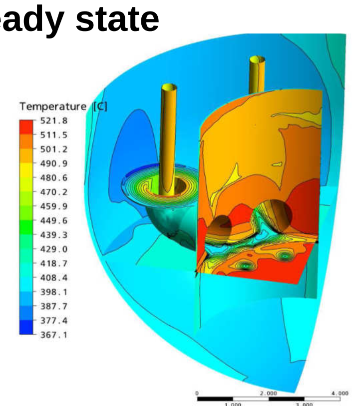
- Can at shut down a safe liquid state be obtained or does somewhere freezing occur (*Pb*<327°C)?
- ELSY model (ANSYS, Böttcher, 2011)
  - $2{\cdot}10^7$ cells, all structures conjugate heat transfer
  - explicit liquid Pb surface modelling
  - heat transfer through structures
  - core modelling- FA's porous body, pressure drop from correlations, decay power as input
  - HEX - porous medium with heat sink
  - pump as momentum source (impeller- non rotating)

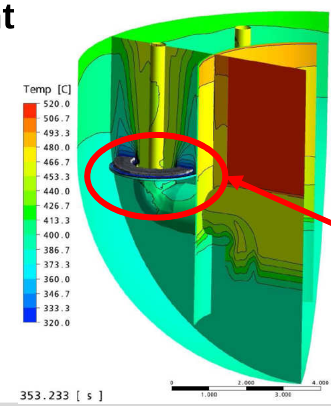




steady state **transient**







local freezing possible for one case
➔design change

Summary- pool thermal hydraulics

Recommendations – NONE

Reasons

- **Validation and verification is still in its infancies.** Correlations for Nu, Δp need to be carefully checked for your case

Trends

- Focus on separate effects to attain V&V in spatial and temporal characteristics
- Current combined numerical & experimental focii
  - wall bounded flows (induced secondary flows by wraps, vanes, corners)
  - flow separation (e.g. backward facing step)
  - shear layers
  - mixing jets (hot into cold, stratific cation
  - transition thresholds al Mixed and natural convection
- Flow and heat transfer patterns in prototypical mock-ups or based on large scale experiments or reactor data (LACANES benchmark, CIRCE, NACIE)

NOTE:

- **Reactor scale simulations are (despite their lack of closed V&V) indispensable indicators for weaknesses of design and operational limits and due to absence of mock-ups the only source of indicative information.**

System Thermal-hydraulics (TH)

Background and purpose

- reactor response to internal&external events in design basis accidents (DBA) such as
  - Flow events (Loss of flow accident-LOFA , Loss of coolant accidents LOCA)
  - Thermal events (transient of overpower, loss of heat sink –LOHS)
  - Station black out
  - ….

➡ safety performance

Approach

- Coupled thermal-hydraulics with neutron kinetics (mostly both simplified)
- Mostly on nodal basis
- prominent system codes (SAS, ATHLET, TRACE, RELAP,SPECTRA, ……)

Trend

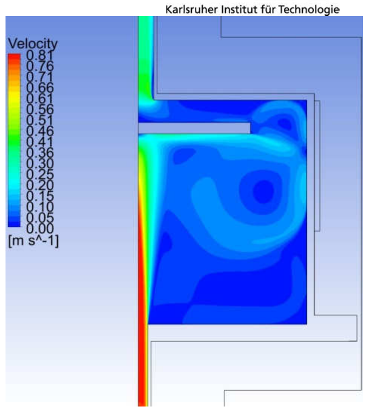
- Coupling System TH with CFD to integrate 3D- local information from CFD to system scale **and**
- Maintain system dynamics

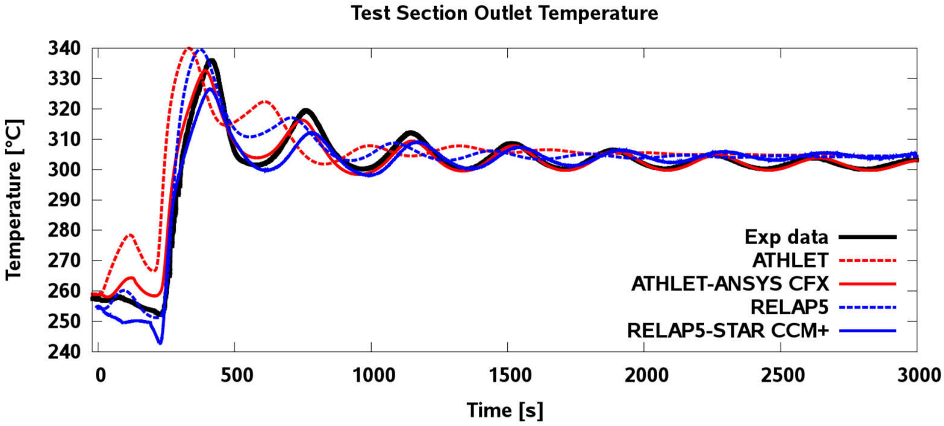
Challenges

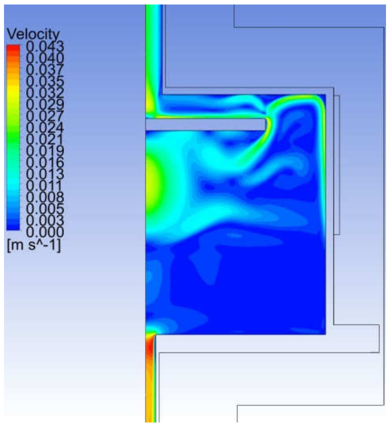
- consistency of physical properties
- selection of coupling locations (limit the amount)
- coupling type implicit vs. explicit (e.g. using external data transfer files)
- domain overlap vs. domain decomposition
- time synchronisation of both codes (master- slave or parallel computing
- tata averaging / Profile generation
- initialisation of both codes ....

System Thermal-hydraulics (TH)

- **TALL-3D benchmark**
  Papukchiev et al. (2015)
  - ATHLET-CFX (GRS)
    - domain decomposition
  - RELAP5-STAR-CCM+ (KTH)
    - domain overlap
  - transient with reversed flow



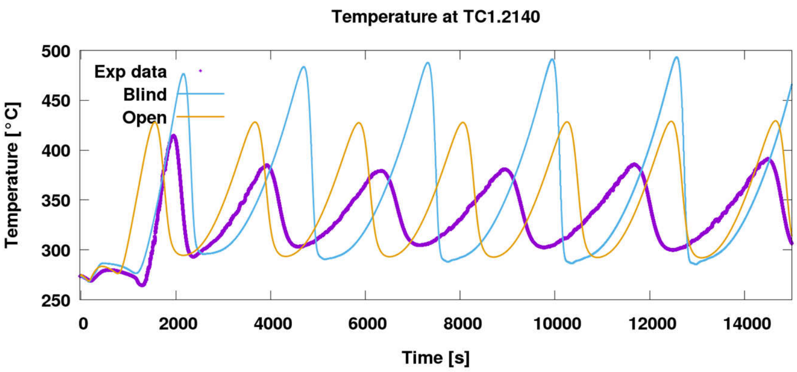


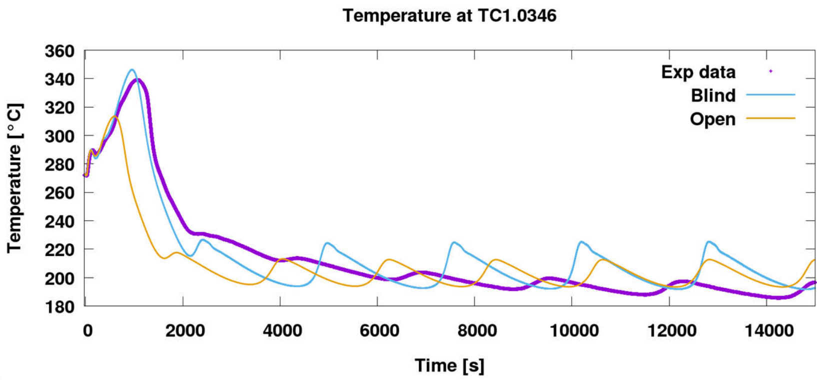


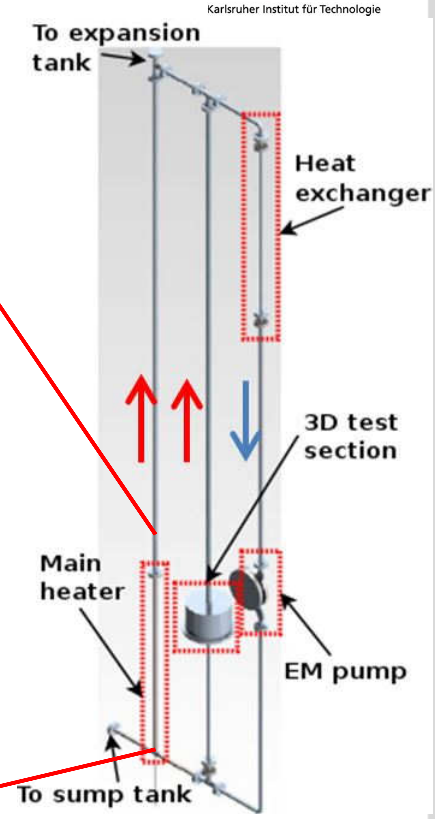
- **good agreement once experimental data are known**

System Thermal-hydraulics (TH)

- blind pre-calculations may exhibit a different picture



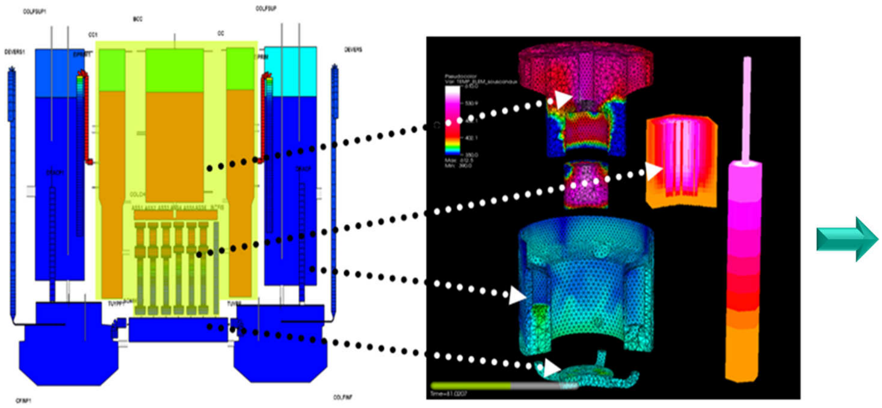




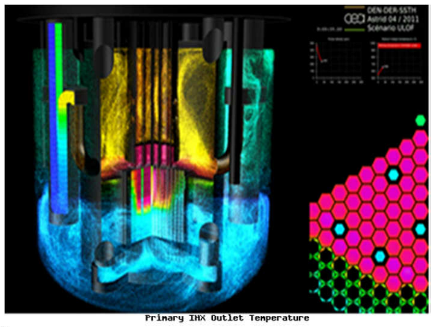
System Thermal-hydraulics (TH)

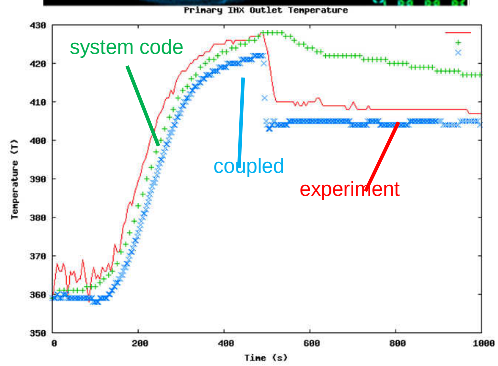
Phenix reactor multiscale analysis

- CATHARE – TRIO_U coupling
- Phenix natural convection test
- low resolution CFD provides valuable improvements compared to system thermal hydraulics
- dedicated post-processing tools enabling 3D visualization (using 3D glasses) of sodium flow patterns in reactor pool



CATHARE   CATHARE –TRIO_U





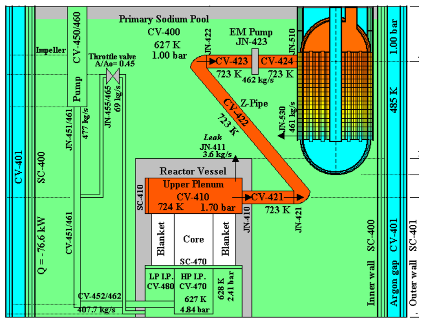
System Thermal-hydraulics (TH)

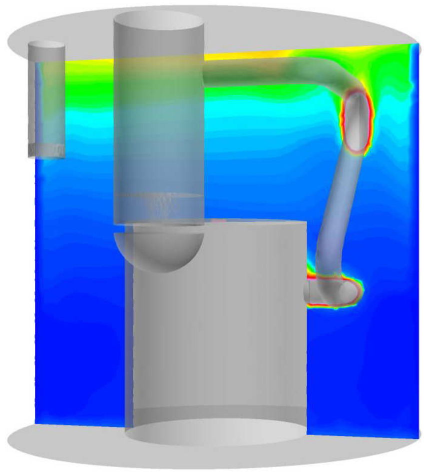
EBR-II example

- coupling of SPECTRA – CFX
- explicit coupling
- domain overlapping technique
- SPECTRA complete system (HEX, opump, pipe)
- CFD only in pool

➡ relatively simple test case, but

➡ demonstrates feasibility of multi-scale approach and allows first validation





Summary- System TH

Recommendations

- **Revisit correlations for Δp and Nu in nodal (1D) system codes according to more recent findings (experiments, DNS data)**

Trends

- include 3D effects from experiments or CFD simulations in STH codes
- consider multi-scale simulation: Couple system TH with CFD
- take care of validation of the coupling methodologies and applications
- validate the transition thresholds from forced to natural convection in the codes
- develop and consistently follow a verification and validation approach (V&V)
- quantify the effect of uncertainties in input data (UQ) could be Monte-Carlo based (as e.g. being used in OECD/NEA UQ benchmark)

Free Surface – TH

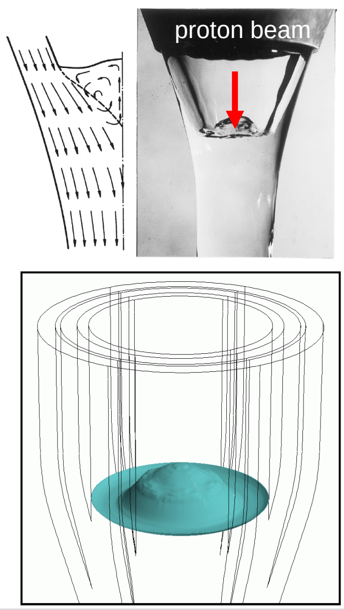
Appearance in reactors:

- gas bubbles in flow (gas entrainment in dome, fuel pin failure causing fission gas release, steam generator tube rupture-pool type reactors)
- ➡ safety relevant due to insertion of positive reactivity into core

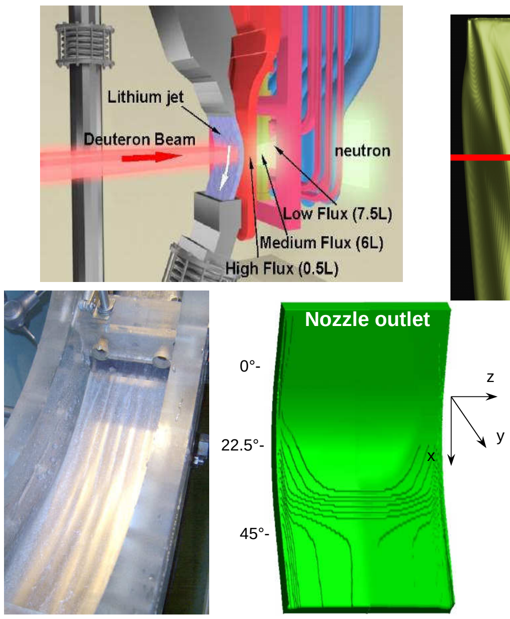
Other nuclear applications

- nuclear targets (neutron production by spallation, ion fragmentation)

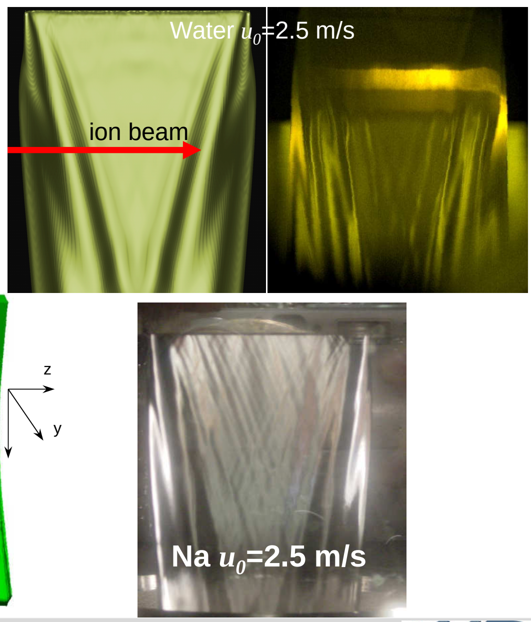
Myrrha-type target



IFMIF-type target



FAIR-type target



Free Surface – TH

Numerical challenges

- different **statistics** of u and h-field (damping times/diffusion times).
- large **density differences** between liquid and gas phase ($\rightarrow\infty$ for vacuum).
- **coupling** of turbulent ***u*-field** with ***h*-field** (lack of adequate models: e.g. level-set methods)
- **scale separation** of u and h (viscosity<<surface tension)
- potential **phase transition** requires LM adapted cavitation models.
- flow mostly **transient** ➡ time step given by p- and u-fluctuations.
- complex geometries induce **secondary flows** (e.g. edges, curved planes) leading to large computation times.

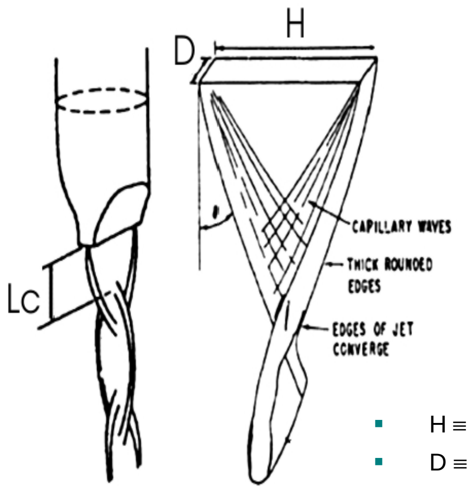
Experimental challenges

- development of free surface detection **sensors** with high temporal & spatial resolution
- lack of experiments with **simultaneous *u* and *h*-field measurements** (unknowns statistics and diffusion times)

Free Surface – TH

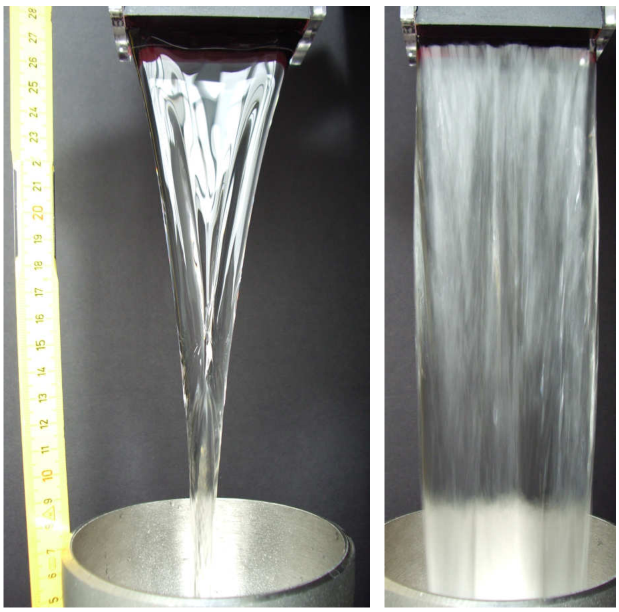
Observations

- Surface tension contracts the stream
- Shear stress/surface tension in causes inversion of jet (twist)
- At discontinuities capillary waves are generated.



- H ≡ jet depth
- D ≡ Jet thickness
- L_C≡ contraction length

$$L_c = \frac{\nu \cdot H}{2}\left(\frac{\rho}{\sigma}\cdot\frac{\pi\cdot D}{16}\right)^{1/2} = \left(\frac{\pi\cdot We}{16}\right)^{1/2}\cdot\frac{H}{2}$$

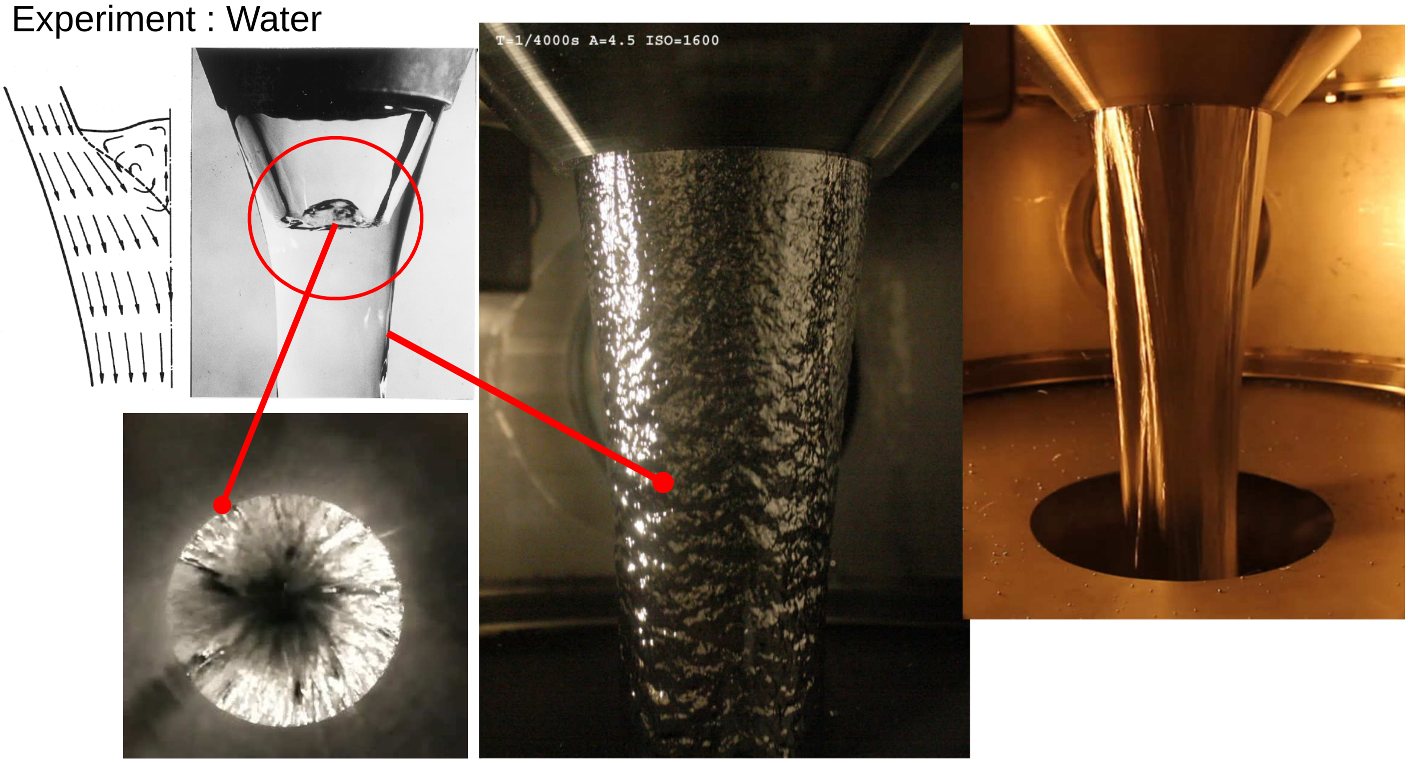


u_0=0.2 m/s   5 m/s

Free Surface – TH -Validation

ADS Windowless Target: 2nd Generation (MYRRHA)

Experiment : Water



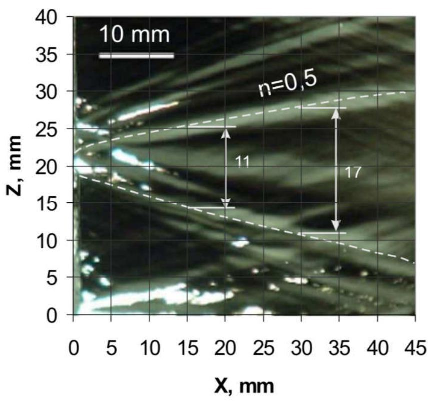
Experiment : $Pb^{45}Bi^{55}$ (top view) Experiment : $Pb^{45}Bi^{55}$ (side view)

Free Surface – TH Validation

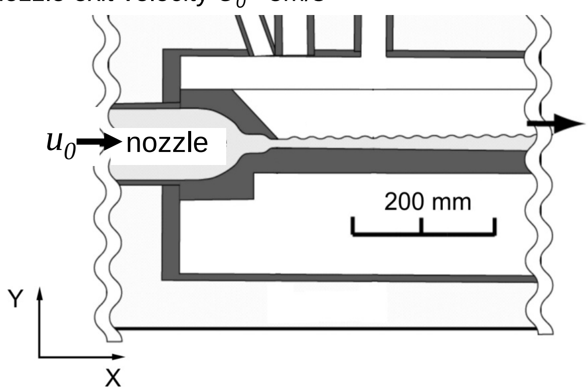
Example:

- Wave propagation on a liquid lithium surface caused by precipitation at the nozzle exit (Kondo et al. (2006) Osaka University)

Experiment **LES** **V2F (unsteady)**



Mean nozzle exit velocity U_0 =5m/s



Results

- Excellent agreement of numerical and experimental data for large scales
- LES allows resolution of fine structure

Free Surface – TH Validation

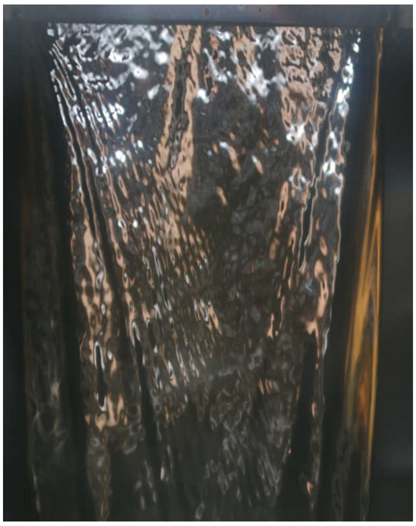
Target development FAIR:

- acceptable agreement of steady state “mean” surface shape
- convective instabilites can be captured by RANS methods
- local unsteady phenomena require an LES

PhD Gordeev,2008;
Daubner, Stoppel, & KALLA DIRAC-Final Report, 2009

Example: sodium jet u_0=2,5m/s





Simulation | Standard photo | High speed cam. (2000fps)

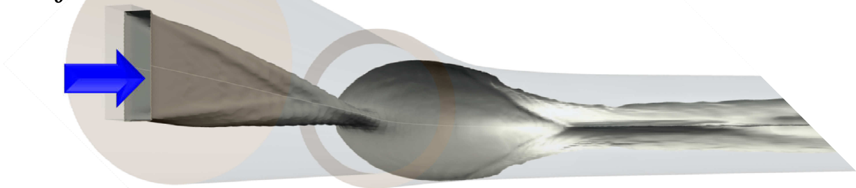
Free Surface – TH Validation

What happens for a free jet impinging on a surface ?

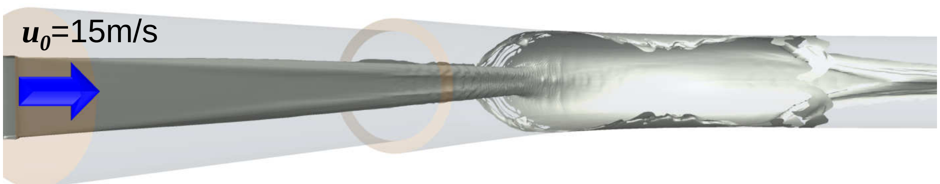
- splashing by momentum exchange
- droplet generation generation
- cavitation ?

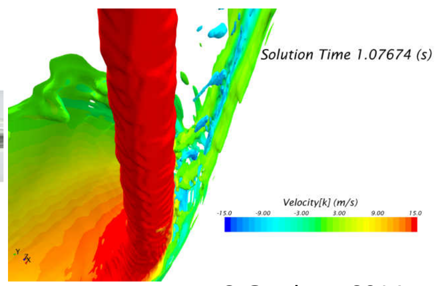
Example: IFMIF –lithium flow entering the catcher
lithium jets with different u_0=5,15m/s , p=10^{-3}Pa

u_0= 5m/s



u_0=15m/s

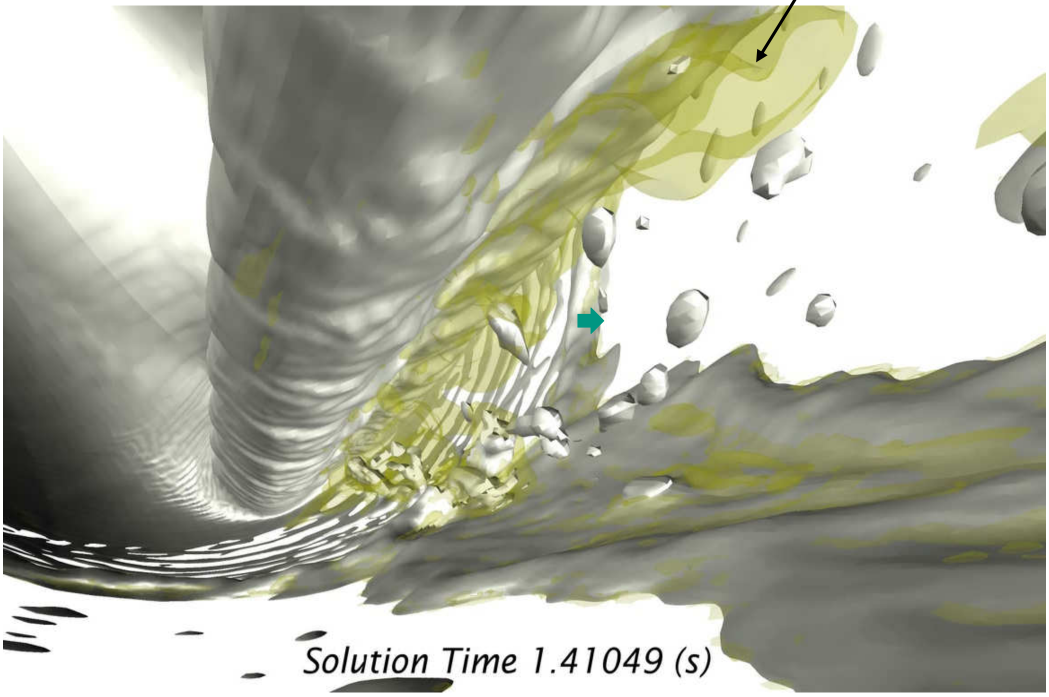




Free Surface – TH Validation

- Conditions: u_0=15 m/s, p=10^{-3} Pa
- Jet flow – Lithium$_{(l)}$ iso-surface VF=0.7

Lithium gas/liquid mixture iso-surface Li$_{(g)}$ 5%



➡ Lithium vapour mainly upstream impingement position

Summary

- Liquid metal flows exhibit features different to normal liquids due to their thermo-physical properties.
- Conventional CFD and system dynamic tools exhibit deficits in simulating heat transfer problems and free surface flows if not liquid metal adapted due to
  - strong anisotropic turbulence due to geometry, heat load,…
  - scale separation of the boundary layers BL (viscous BL<< thermal BL,…)
  - deficits of adequate coupling of free surface with turbulence modeling
- Recent progress in measurement techniques enables access to rather complex flow phenomena.
- Development process allows to define generic experiments focussing to
  - develop more advanced physical models.
  - generate a data base, local correlations for design of complex systems.
- Each liquid demands a dedicated material study to ensure a safe life time performance especially in a nuclear environment

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