Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

KArlsruhe Liquid Metal LAboratory
KALLA

Turbulenter Impuls- und Wärmetransport in Flüssigmetallen- Experimentelle Methoden und Berechnungsansätze

Stieglitz, R.
Batta, A., Grötzbach, G., Class, A., Daubner, M., Lefhalm, C.-H., Otic, I.
and the KALLA team
Institute for Nuclear and Energy Technologies (IKET)
Forschungszentrum Karlsruhe GmbH

Content

- Technical appearance of liquid metal flows
- Specific properties of liquid metals
- Turbulent heat exchange
  - Analogies between momentum and heat exchange
  - Experimental observations in a heated pipe
  - Closure methods for turbulent heat flux
- Measurement techniques in liquid metals
- Engingeering applications
  - The heated pipe am old story
  - Heated Rod in a cylindrical cavity in KALLA
  - MEGAPIE target
- SUMMARY and outlook

Technical Liquid Metal flows

- Liquid metals are known to mankind since about 6000 years (natural Mercury)
- They are refined and casted since more than 4000 years (bronze, copper)
- Production of iron started in Turkey since 3000 years
- Alumina and alloy production on large scales in the last 200years

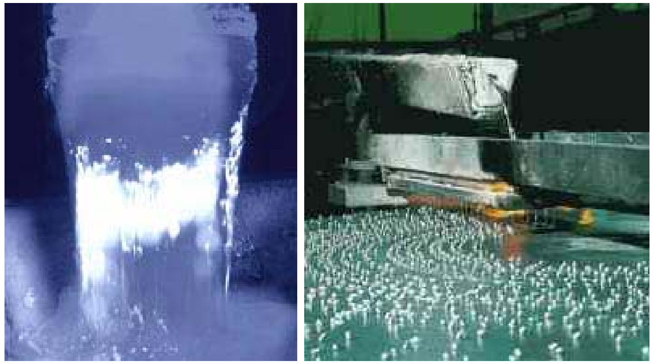

Liquid mercury in glass capsule


Bronze casting


Raw iron refinement

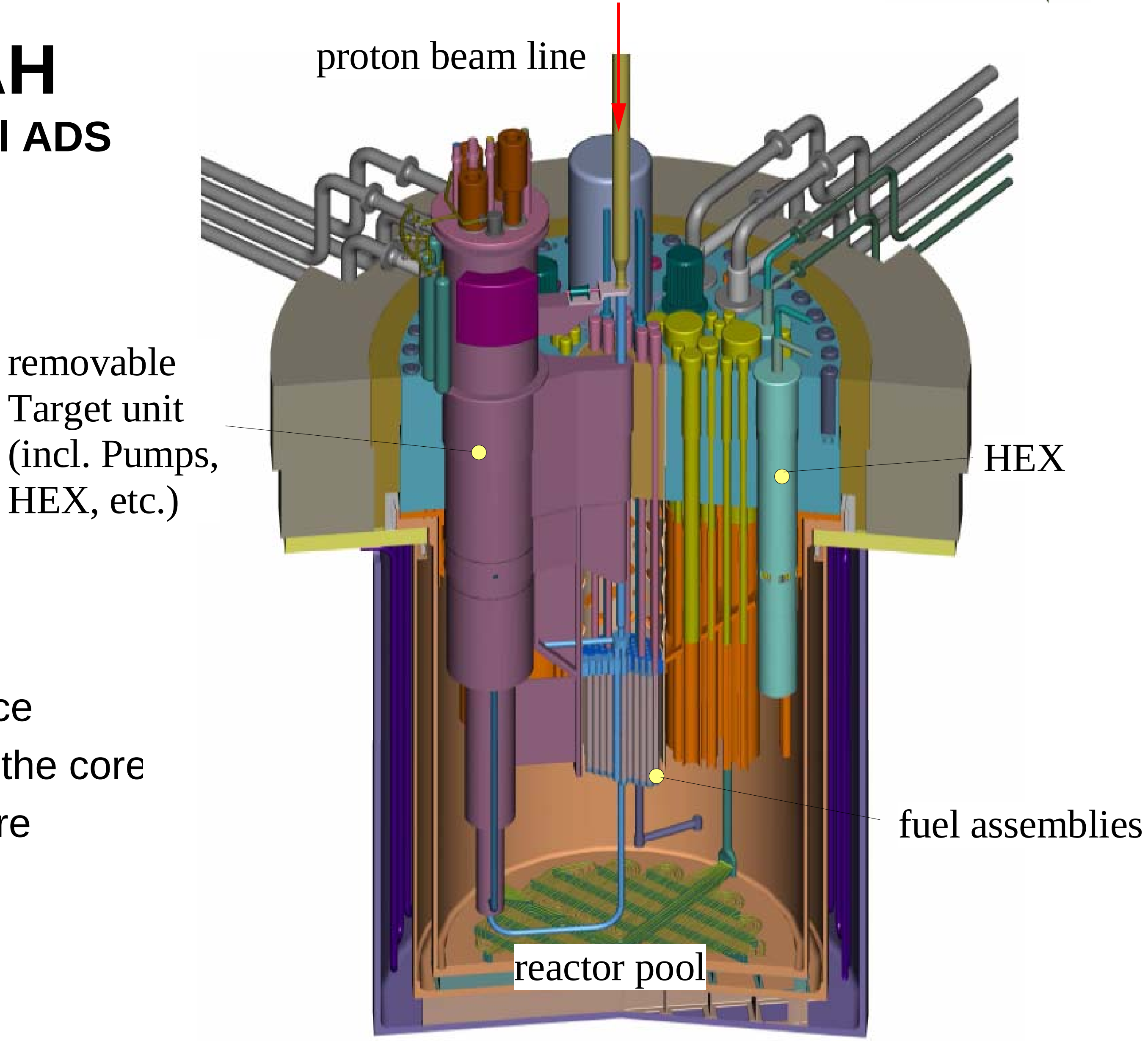
- Current industrial interest:
  - Adaptive materials with certain properties for specific use in e.g. car insdustry, aeronautics, etc. like AlLi-alloys
  - Minimization of primary energy input during refinement
  - Higher demand on quality of surfaces and reduction of number of secondary machining processes

Requirements:
Measurement techniques, heat transport phenomena,
phase change problems


Alumina preparation for casting

FISSION: MYRRAH

- a planned 50MW Experimental ADS



Features

- Free surface target
- Criticality k_{eff}~0.95
- Thermal power P_{th}=50MW
- Proton beam 350MeV at 5mA
- Lead bismuth cooled

Critical thermal hydraulic issues

- Free surface flows with turbulence
- Mixed convection (Buoyancy) in the core
- LM technology in Target and Core
- Instrumentation and monitoring

Specific properties of liquid metals

GENERAL FEATURES

- opaque, totally reflecting
- high temperatures,
- corrosive,
- large surface tension
- high thermal conductivity

HEAVY LIQUID METALS

- high density
- low kinematic viscosity,

		Unit	Pb^{45}B^{i55}	Lithium	Water
			300°C	300°C	25°C
density	ρ	[kg/m^3]	10325	505	1000
heat capacity	c_p	[J/(kgK)]	146.33	4279	4180
kinematic viscosity	ν	[m^2/s]$\cdot 10^{-7}$	1.754	9	9.1
heat conductivity	λ	[W/(m K)]	**12.68**	**29.2**	0.6
electric conductivity	σ_{el}	[A/(V m)]$\cdot 10^5$	**8.428**	**33.5**	$2\cdot 10^{-4}$ (tap)
thermal expansion coefficient	α	/	**$6.7\cdot 10^{-3}$**	**$43.6\cdot 10^{-3}$**	$6\cdot 10^{-3}$

Specific properties of liquid metals

Force ratio		$X_{PbBi(300°C)}$/ $X_{Water(25°C)}$	$X_{Li(300°C)}$/ $X_{Water(25°C)}$	Energy ratio		$X_{PbBi(300°C)}$/ $X_{Water(25°C)}$	$X_{Li(300°C)}$/ $X_{Water(25°C)}$
Reynolds	$\mathrm{Re}=\frac{u\cdot l}{\nu}$	**5**	0.98	Peclet	$Pe=\frac{u\cdot l}{\kappa}$	**0.017**	**0.01**
Grashof	$Gr=\frac{g\cdot\alpha\cdot\Delta T\cdot l^3}{\nu^2}$	**30**	**7.4**	Fourier	$Fo=\frac{l^2}{\kappa\cdot t}$	0.017	0.01
Prandtl	$\mathrm{Pr}=\frac{\nu}{\kappa}$	**0.003**	**0.008**	heat conduct. $[m^2/s]$	$\kappa=\frac{\lambda}{\rho\cdot c_p}$	**58.5**	**94.1**

- Scale separation of thermal and viscous boundary layer

Strategy (EU, HGF and internal programs)

- Liquid metal adapted heat transfer models (several approaches possible)
- Detailed measurements in simple geometries (model development and verification, statistical features of u and T, measurement technology)

Turbulent heat transfer

- Turbulent energy equation

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

- Analogous to the turbulent viscosity $\varepsilon_M=\mu_t/\rho$ a turbulent heat flux appears and thus
- a turbulent eddy heat diffusivity $\varepsilon_H=\lambda_t/(\rho\, c_p)$ can be defined, the ratio is called
- the turbulent Prandt number Pr_t

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

Consequences

- Pr_t is far of being a constant (in reality a tensor)
- Difficult to measure directly (measure of dimensions and available sensor sizes, temporal resolution)
- Involves several modelling problems

Turbulent heat transfer

Closure methods for turbulent heat flux

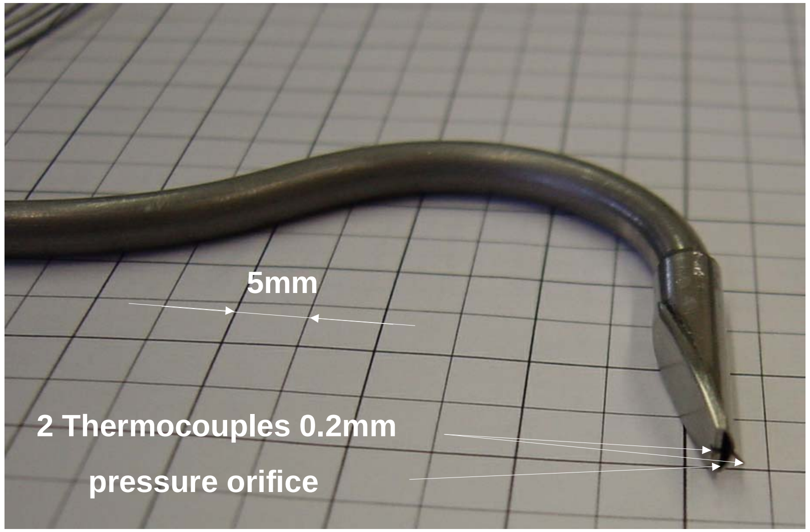
- Semi-empirical models of zero and first order developed since late fourties yield mostly to **Reynolds analogy** results and to $Pr_t = f\,(Pr,\ \varepsilon_M/\nu)$ (momentum-field≈temperature field)
- Turbulent Prandtl Pr_t number from analytic solutions account for the statistics of the turbulence field (see Yakhot et al., 1987), but only applicable to simple geometries problematic with buoyant flows.

$$\left[\frac{\left(Pr_{eff}^{-1}-1.1793\right)}{\left(Pr^{-1}-1.1793\right)}\right]^{0.65}\left[\frac{\left(Pr_{eff}^{-1}+2.1793\right)}{\left(Pr^{-1}+2.1793\right)}\right]^{0.35}=\frac{1}{\left(1+\varepsilon_M/\nu\right)} \quad \text{with} \quad Pr_{eff}=\frac{\left(1+\varepsilon_M/\nu\right)}{\left(\frac{\varepsilon_M/\nu}{Pr_t}+\frac{1}{Pr}\right)} \quad .$$

- Turbulent heat transport modelling by means of transport equations (e.g. the turbulent fluxes $\overline{u_i'T'}$ temperature variance $\overline{T'^2}$, and its dissipation $\varepsilon_{T'}{}^2$ (TMBF –model) but each higher level of modelling leads to new constant and triple correlations a priori not known.
  Potential Solution approach:
  Determination of constants and triple correlations from
- Direct numerical simulation of the temperature field in simple geometries
- CURRENT STATUS: sophisticated models for *u*-field but 0-dim. for T-field

Velocity: Intrusive methods

- Pitot and Prandtl tubes



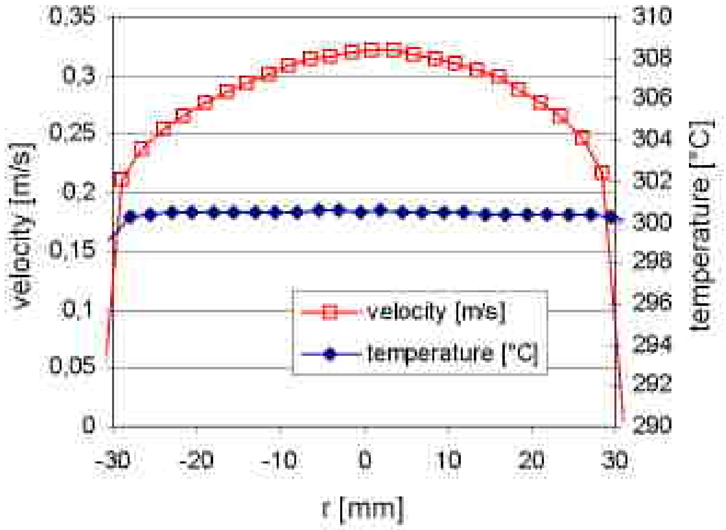
measurement of pressure or pressure differences in fluid domains (coupled with TC)

<u>Advantages</u>

- Sufficient time resolution
- Simple set-up

<u>Disadvantages</u>

- Disturbance of flow (intrusive method)
- Limited spatial resolution (boundary layer)
- Several corrections required.
- High fabrication effort in miniaturizing
- Sophisticated fill and drain necessary.
- Variable measurement ranges necessary for resolution of smallest fluctuations.
- Only one component measurable (flows in complex geometries ?)



Velocity :Ultra-Sound Doppler Velocimeter (UDV)

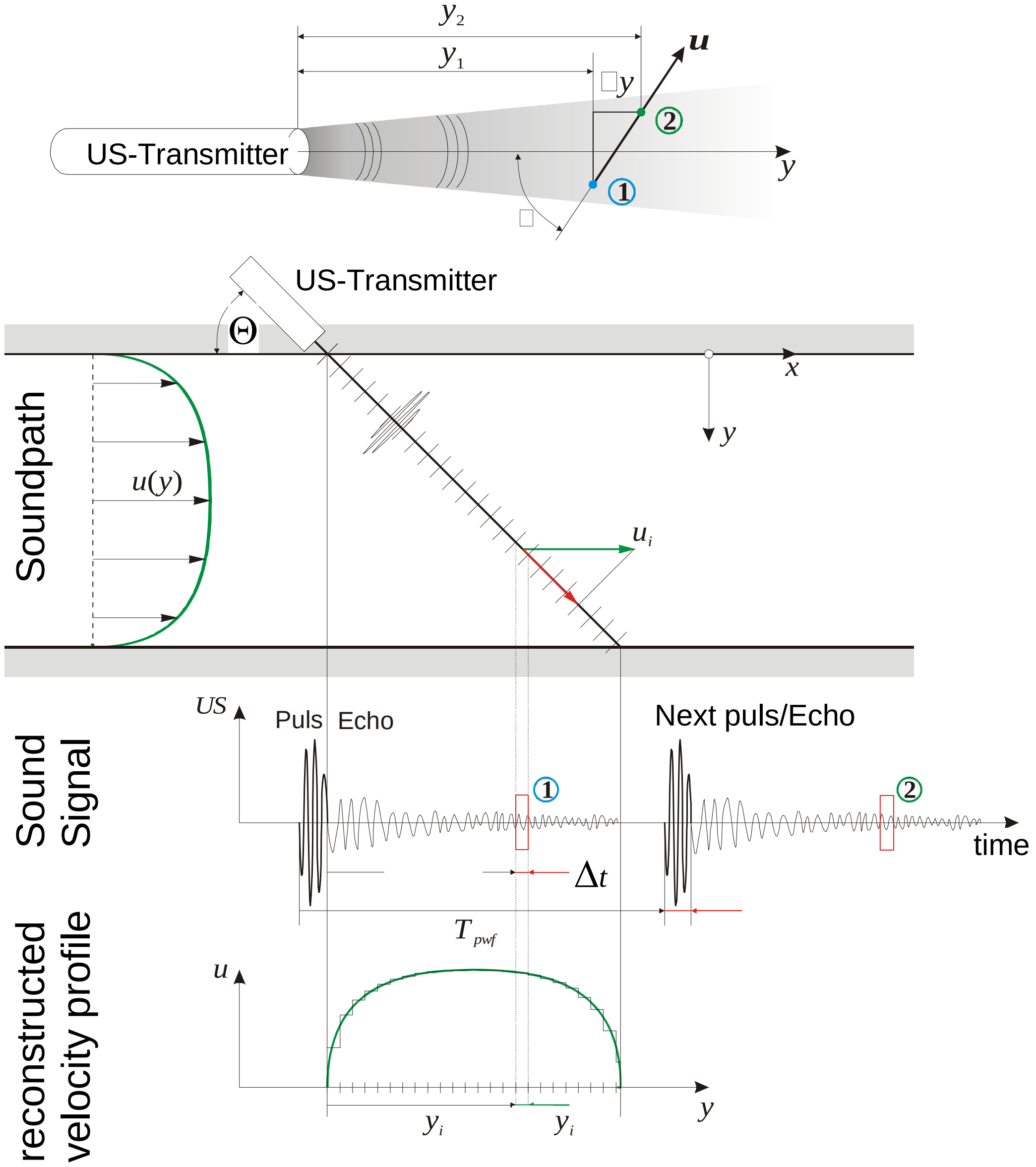
Principle (particle tracking)

- Distance change from sensor due to motion from 1→2 between two pulses.
- Determination of the time difference from the phase shift between received echoes

⇨ Velocity at a discrete distance

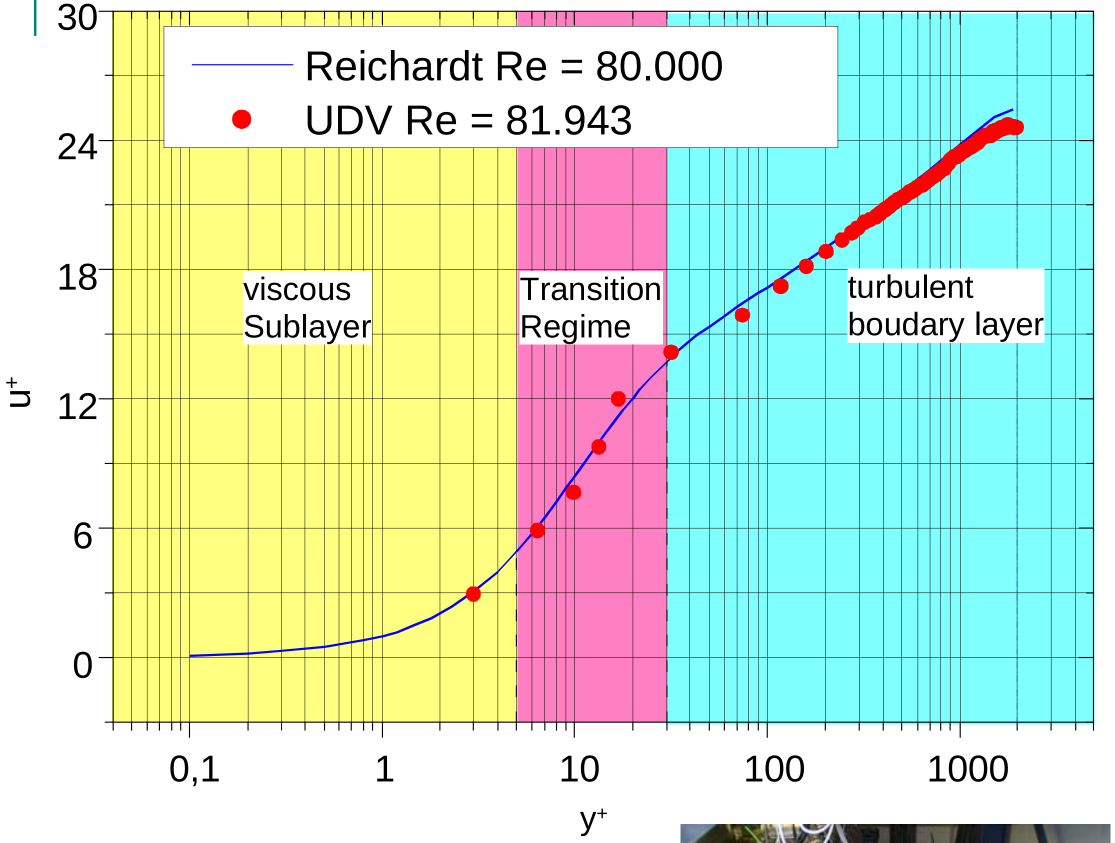
Profile

- Separation of sound path in time intervals (gates Δt) allows recording of a velocity profile. Therefore,
  - Coupling of a time t_i with a measurement position
  - Determination of the local velocity u_i in the interval i



PhD Thesis C.-H. Lefhalm 2004

Velocity: Ultra-Sound Doppler Velocimeter (UDV)



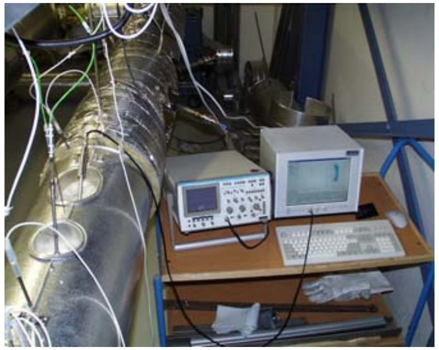
Result in the boundary layer

- All parts of the viscous boundary captured by UDV
- Max. deviation in the transtion regime of 5%
- UDV-measurements possible into the viscous sublayer (y$^+$=3   ~46μm)
- Temporal resolution currently up to 30Hz

Problems

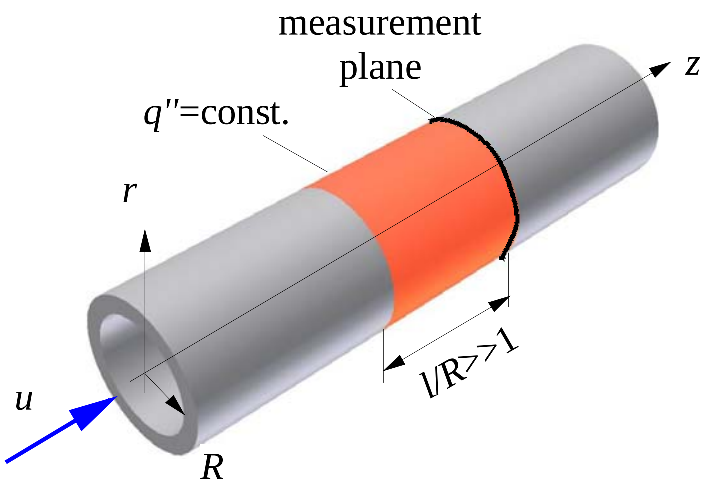
- Long-term wetting of the sensor
- Temporal resolution (Turbulence spectra)
- What are the scattering particles ?
- More effective wave guides (Temperature, sound losses)
- Enhancement of math algorithm effectivity
- Only applicable in isothermal flows.
- Only one velocity component (3D-flows ?)

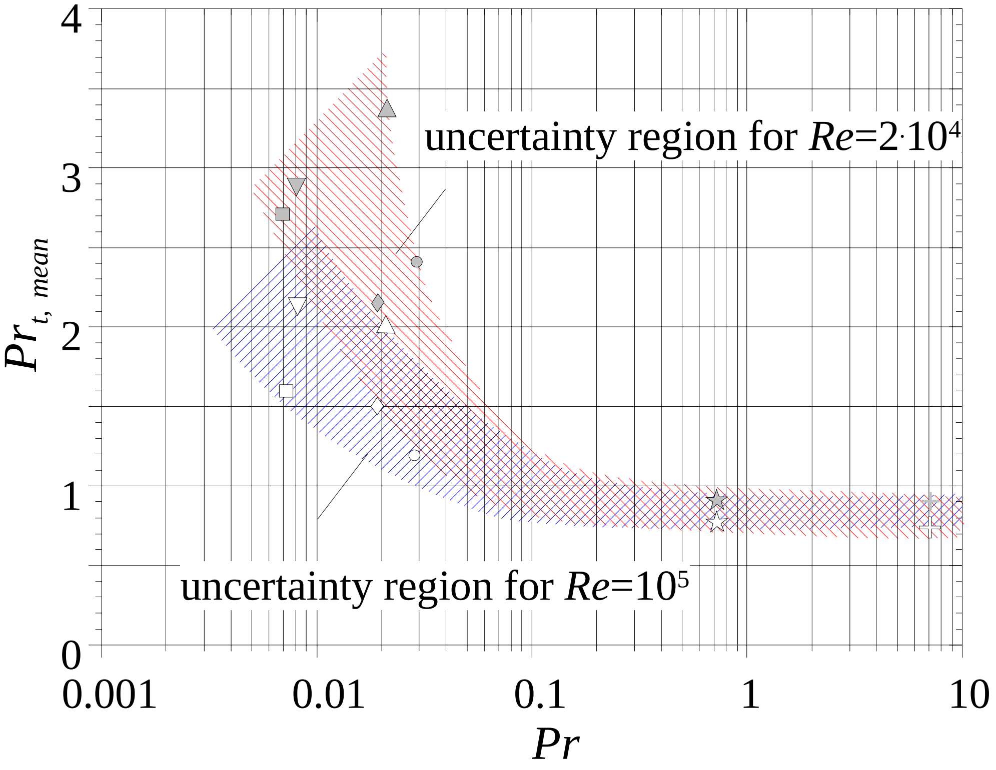
UDV-Sensor developed
in cooperation with
FZR



The Heated Pipe- “An old Story”

- Fully developed turbulent (hydraulically and thermally) flow heated with a constant heat flux at different Reynolds (*Re*) and molecular Prandtl numbers (*Pr*)

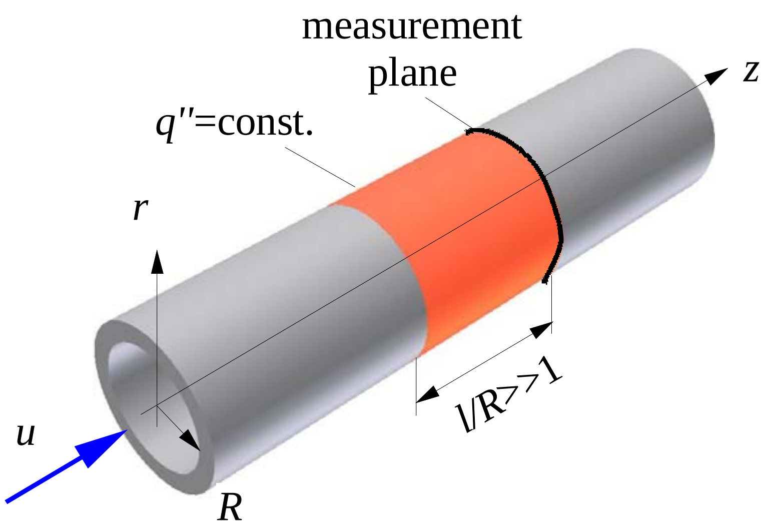


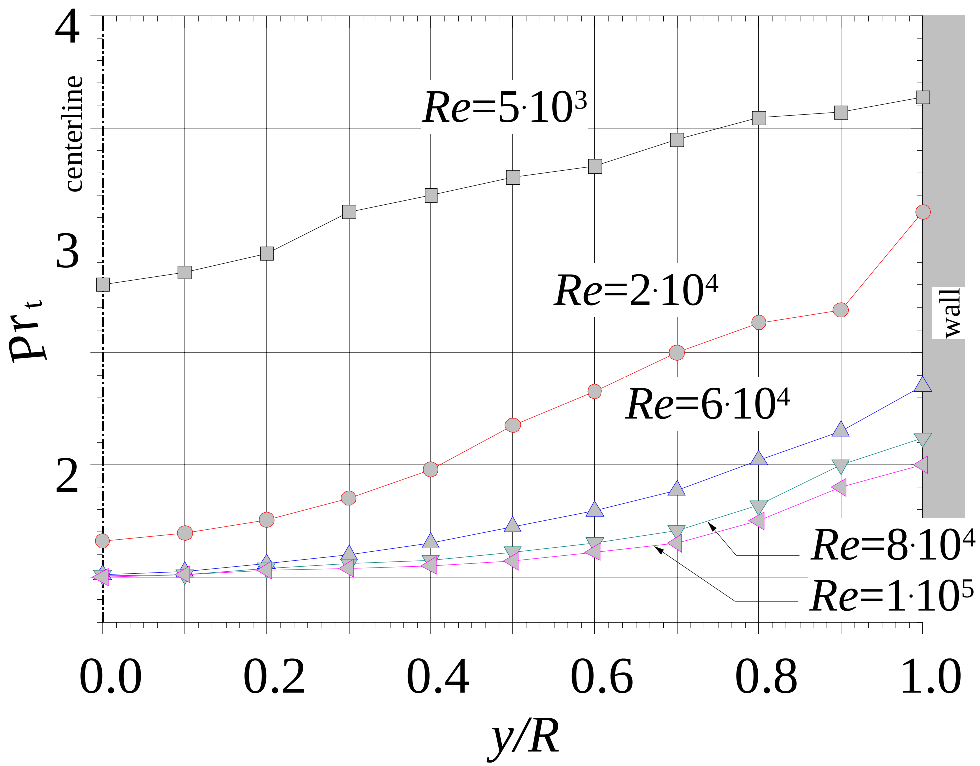


- Result:
  - Mean turbulent Prandtl number ($Pr_{t,mean}$) depends on molecular Prandtl number *Pr*.
  - Mean turbulent Prandtl number ($Pr_{t,mean}$) is a function of the Reynolds number *Re*.
  - But, for model development an unacceptably large uncertainty exists.

The Heated Pipe- “An old Story”

- Measured local turbulent Prandtl number (Pr_t) in a fully developed turbulent flow heated with a constant heat flux at different Reynolds (Re)

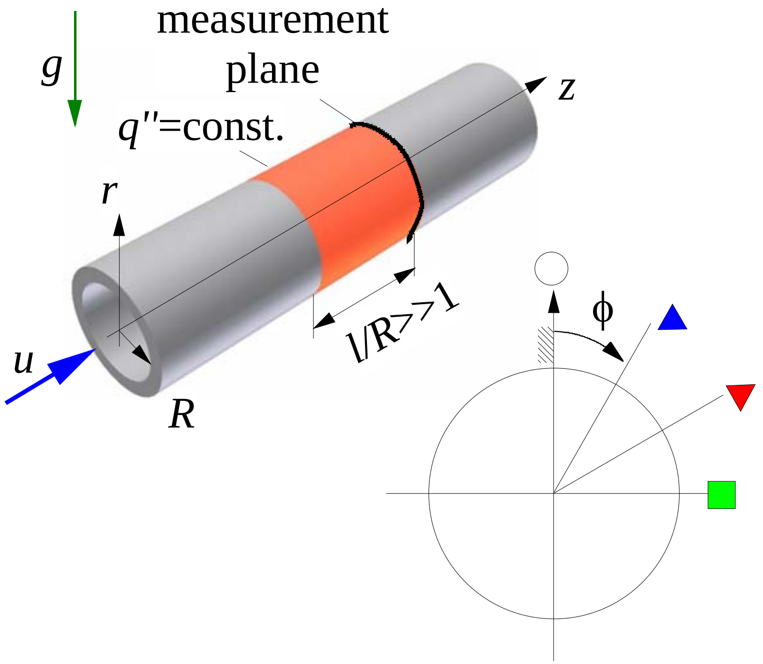


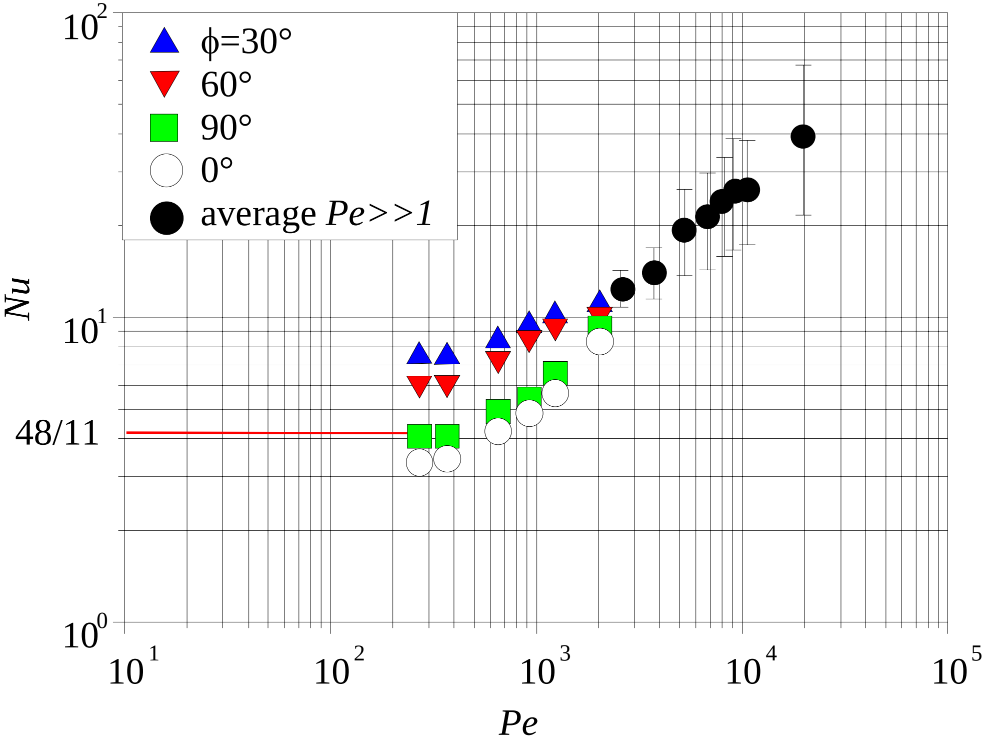


- Result:
  - Local turbulent Prandtl number (Pr_t) is a function of the Reynolds number Re **and** the radial coordinate y/R.
  - But, be careful with experimental data because boundary conditions and buoyancy play a considerable role.

The Heated Pipe- “An old Story”

- The problem of free convection distortion. Liquid metals exhibit due to their large thermal expansion and low kinematic viscosity buoyancy distortion effects even at large *Re* (Hg, PbBi at *Re*>10^5)
- The horizontal pipe

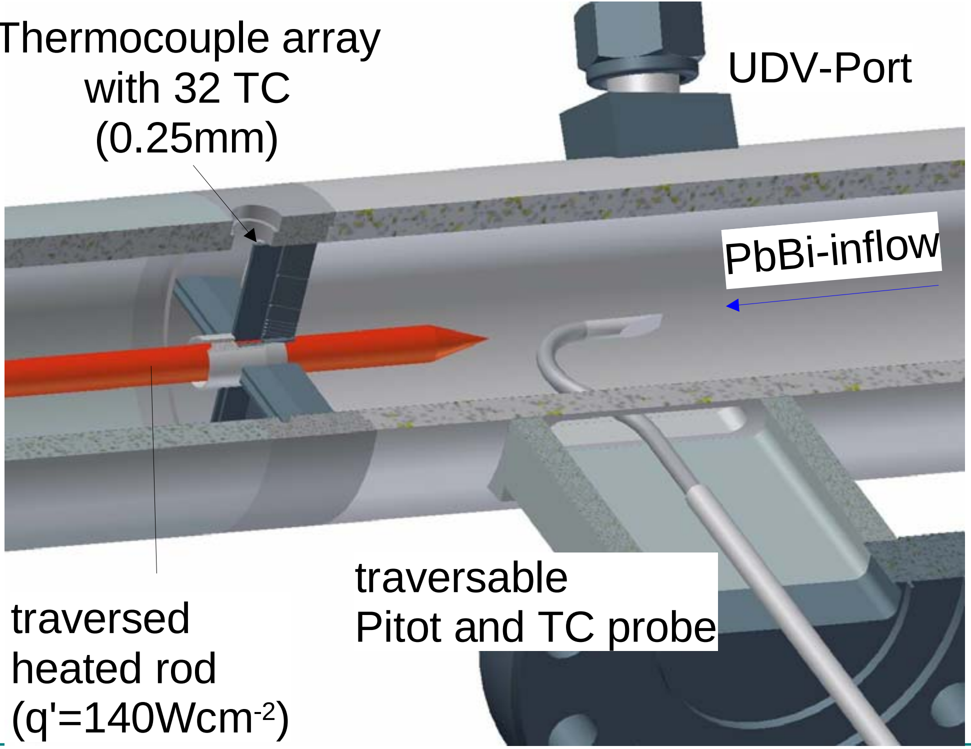




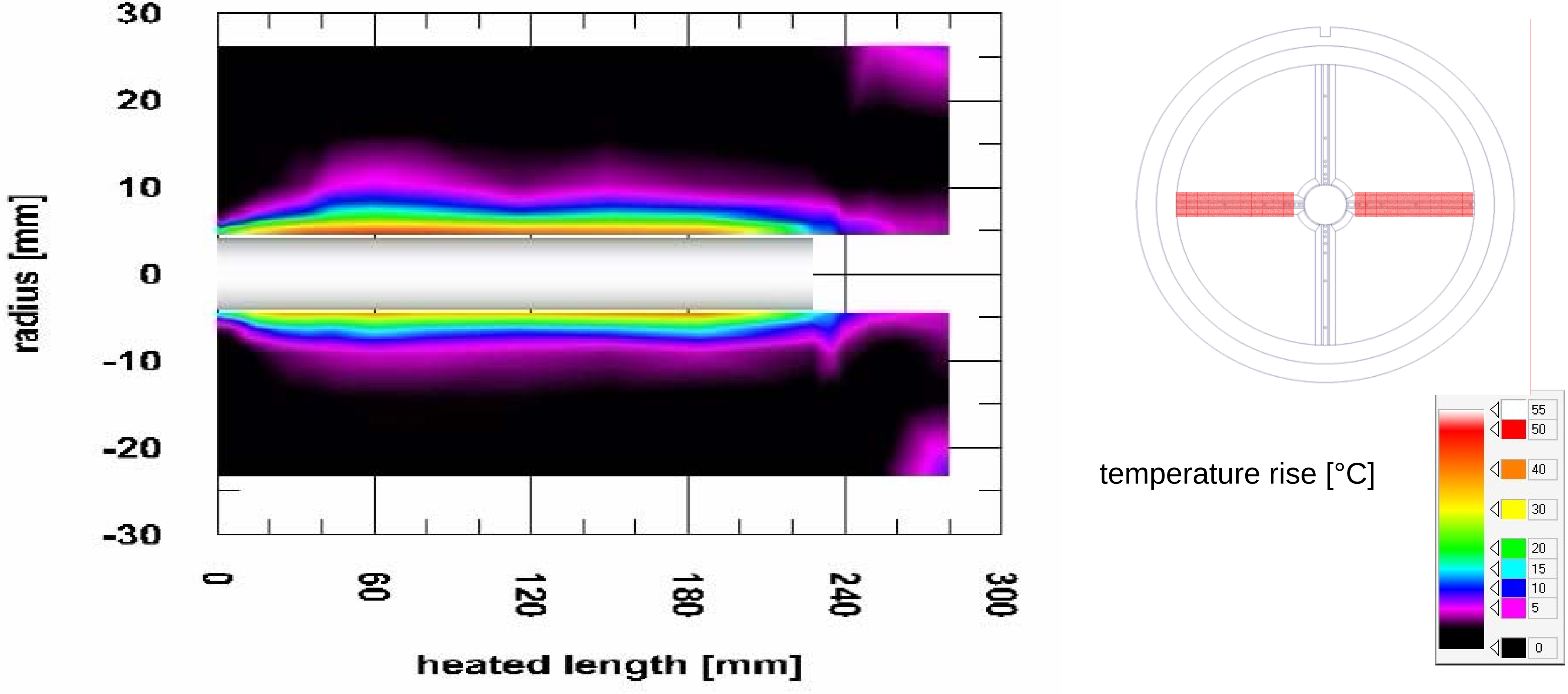
- Result:
  - Even large *Re* does not ensure a pure forced convective flow.

The Heated Rod in THESYS(KALLA)

- Fully developed turbulent flow facing a heated rod concentrically in an annular cavity.
- Horizontal arrangement with defined boundary conditions regarding
  - Detailed measurement of the inflow velocity profile
  - Local velocity and temperature measurements.
  - Heat balance and heat loss evaluation (monitoring temperatures at outside insulation).
  - Pre- and post test analysis of the test section.
- CFD analysis with commercial code packages using different turbulence models.



Temperaturfield along the Heated Rod

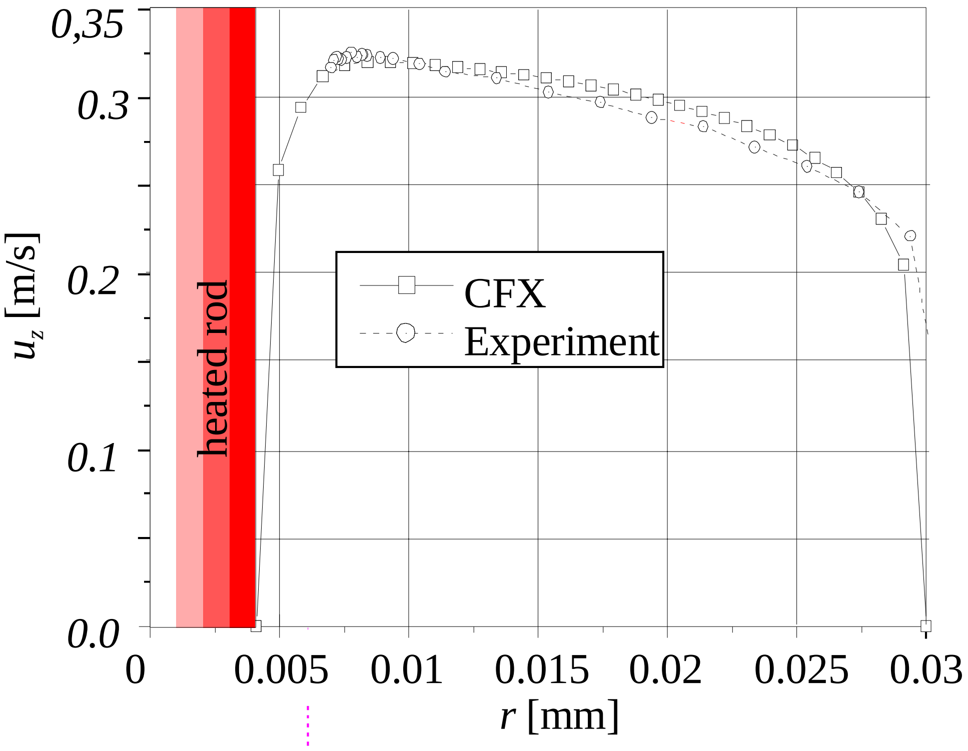


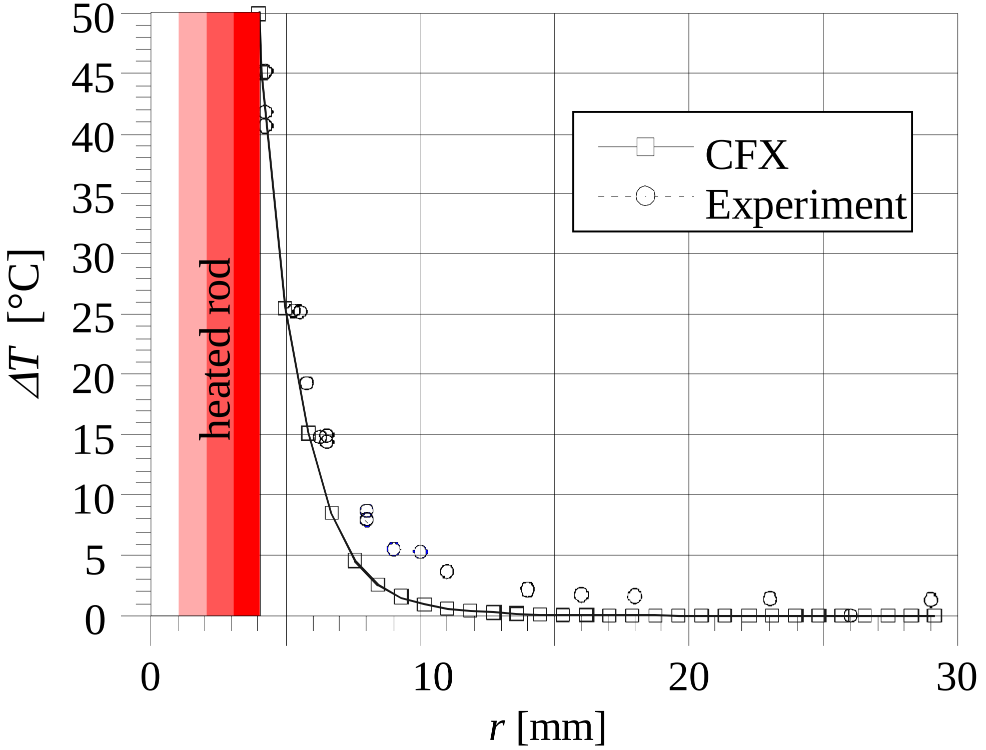
Conditions: $Re = 10^5$, $P_{HR} = 2kW$, T_{in}=300°C

- Only in front part a symmetric temperature profile
- Distortion of the temperature field for z/d >13.9 (asymmetry of rod, buoyancy)

The Heated Rod-CFD

- CFD with SST-model (k-Ω-model near wall and k-ε in the bulk), y^+~1 in heated part, but use of Reynolds-analogy between u and T field with a prescribed and constant Pr_t (mostly Pr_t =0.9),





Conditions: Re = 10^5, P_{HR} = 2kW, T_{in}=300°C at z/d=13 (half heated length)

- Coincidence of measured and computed velocity.
- Resonable temperature agreement of CFD with Experiment at fluid- wall interface. But,
- Thermal boundary layer is thicker in experiment like expected (different heat fluxes).

MEGAPIE – Liquid metal cooled “Beam window”

Features

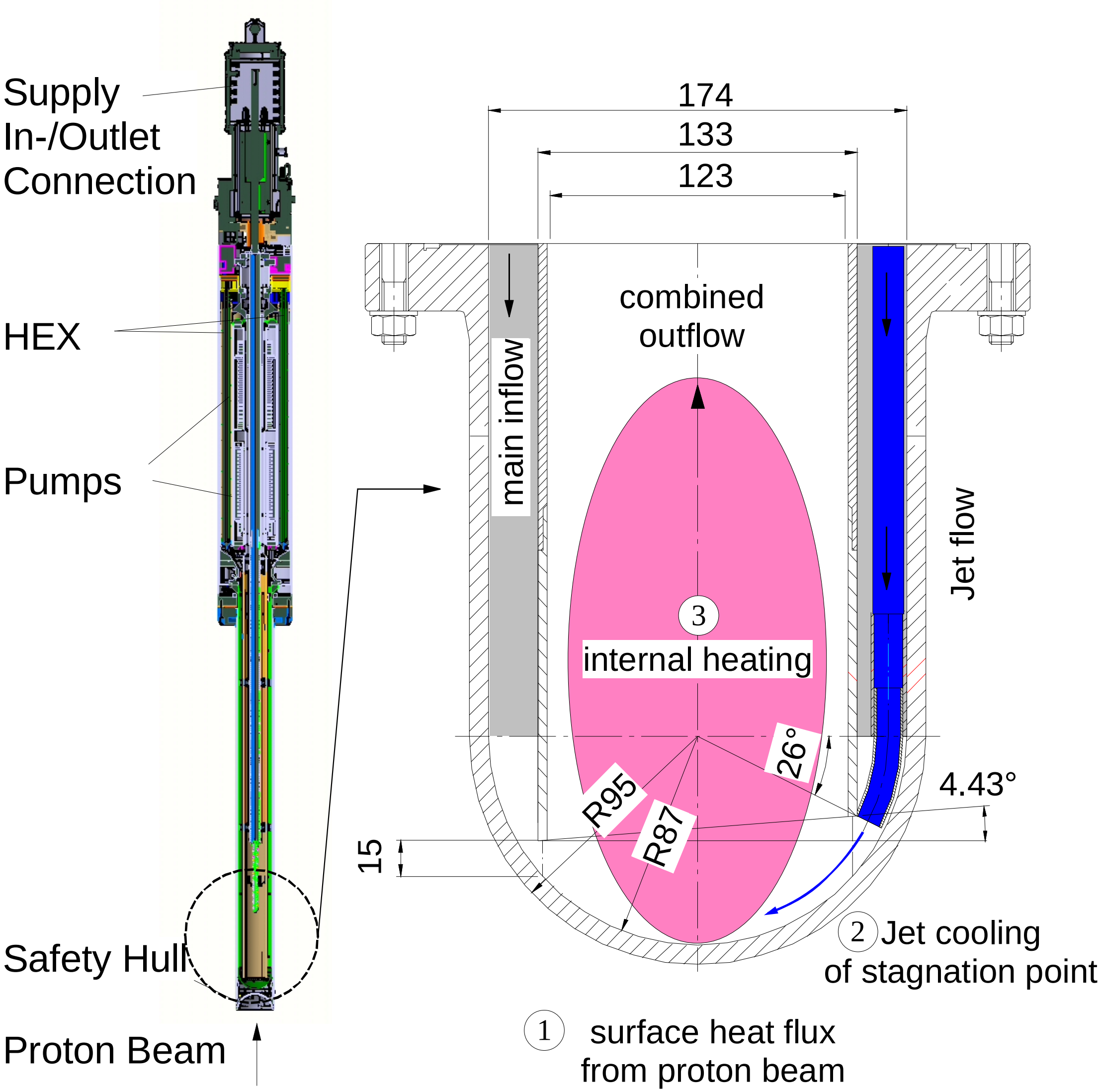
- 1MW power release in spallation target
- 82 litres PbBi-inventory containing pump, HEX,cover system, etc.

THERMALHYDRAULICS

- Complex flow in 3D geometry
- Internal heat generation by spallation reactions (85-92%).
- Surface heat removal from proton heated “beam window” (8-15%).
- Jet cooling of stagnation point (turbulent mixing of heat by cross flow).

AIM

- Spallation demonstration
- Neutron source for Physics
- Full power operation since Aug. 2006

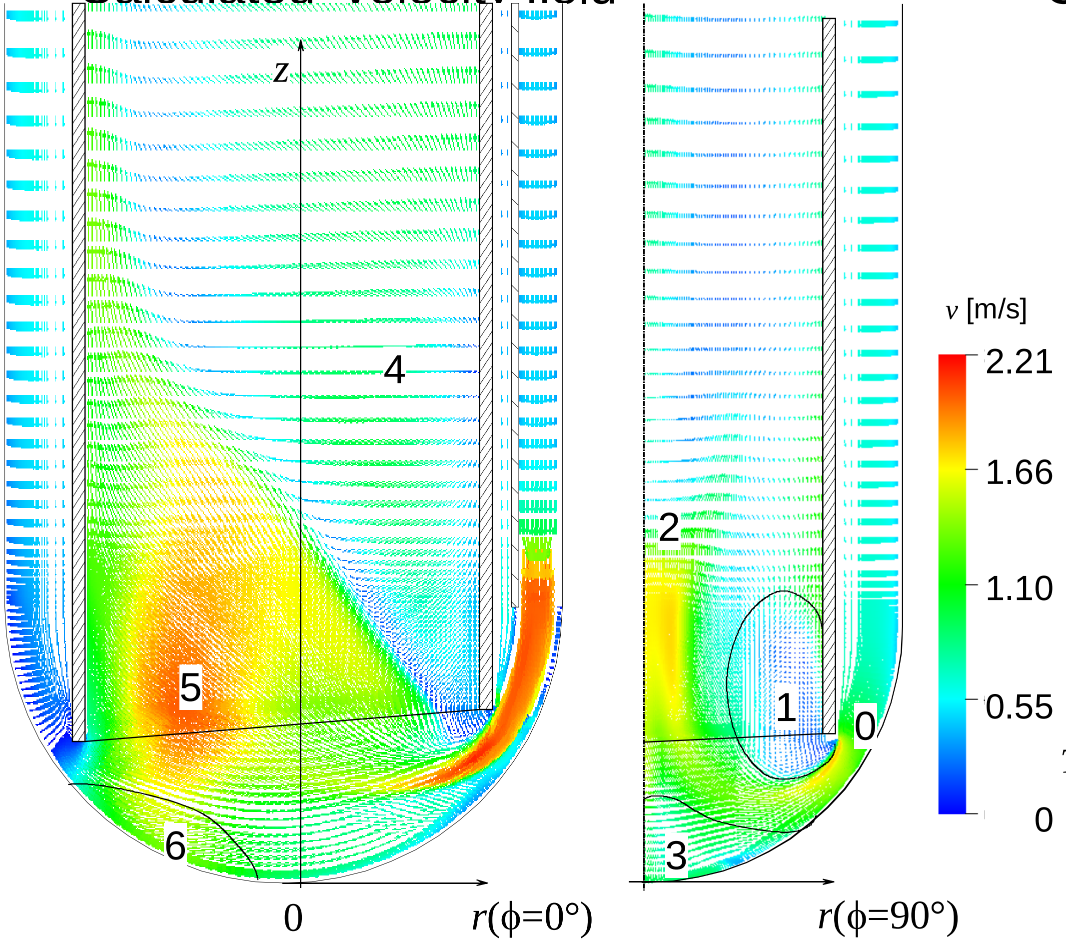


MEGAPIE-Simulation-Heated Jet Experiment

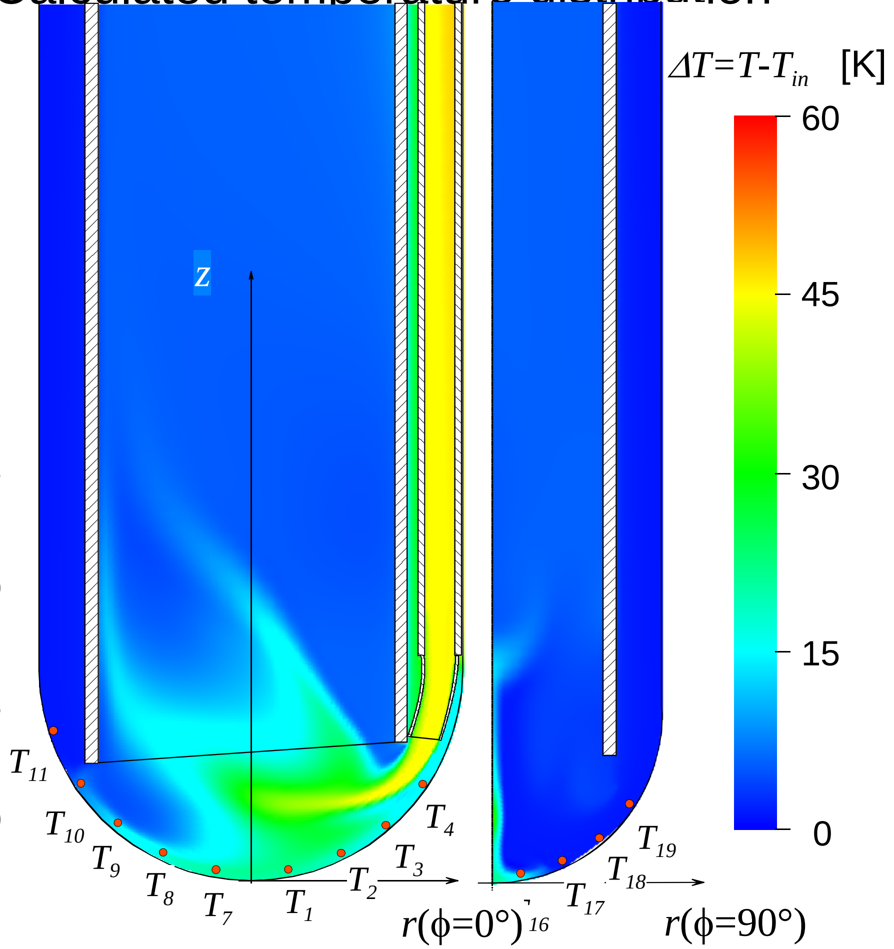
CFD (SST, Reynolds –analogy, symmetry assumption) simulation of the

- momentum field in a complex geometry and the corresponding
- temperature field.

Calculated velocity field

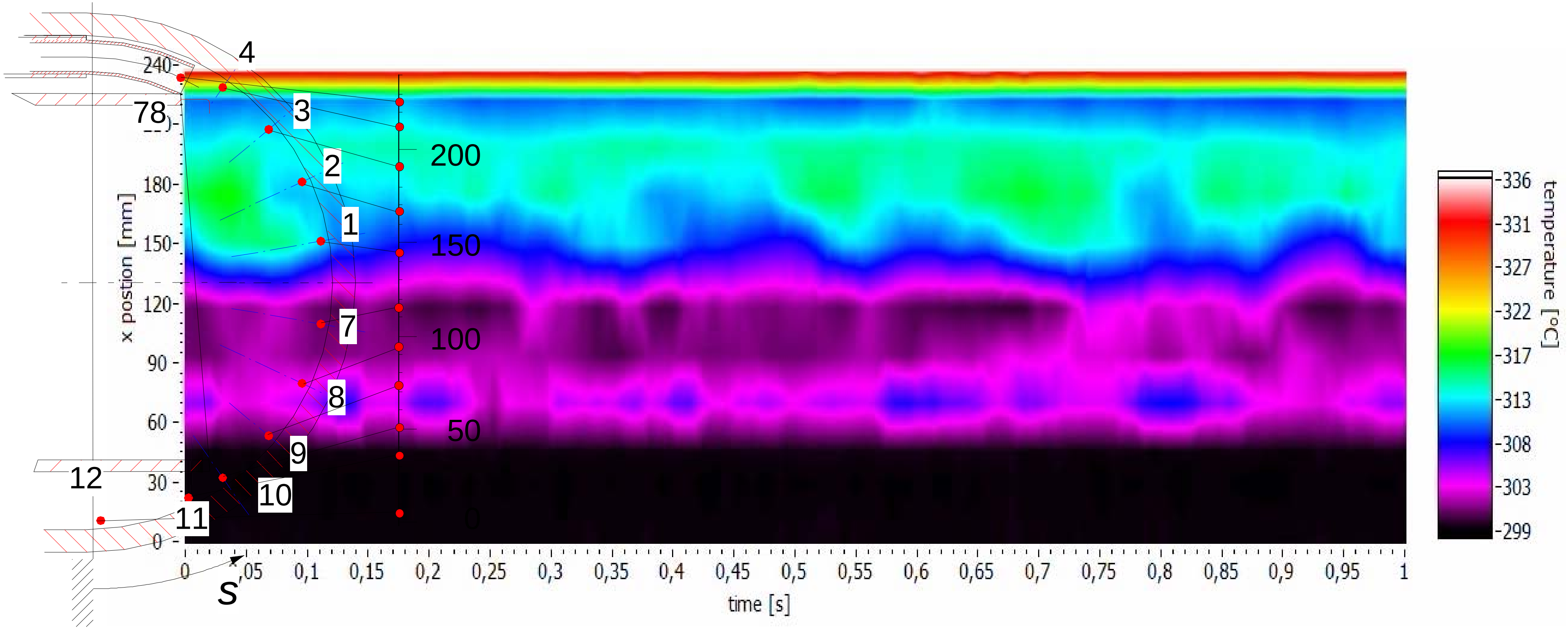


Calculated temperature distribution



MEGAPIE -Heated Jet Experiment

Temporal behavior of the temperature distribution at the lower shell in nozzle plane for Q_{main}=18m³/h, Q_{jet}=1.2m³/h, T_{in} =300°C, T_{jet}=360°C, $f_{recording}$=128Hz.



- Jet impinging the lower shell 60mm away from center line and splitting up into different streams.
- Part of jet stream hitting shell opposite the nozzle exit.
- Temperature field time dependent at nominal operation conditions strong fluctuations at centerline ((→LES)

Daubner, Batta et al. J. Nuclear Materials, 335, p.286ff, 2004.

MEGAPIE-CFD-EXPERIMENT

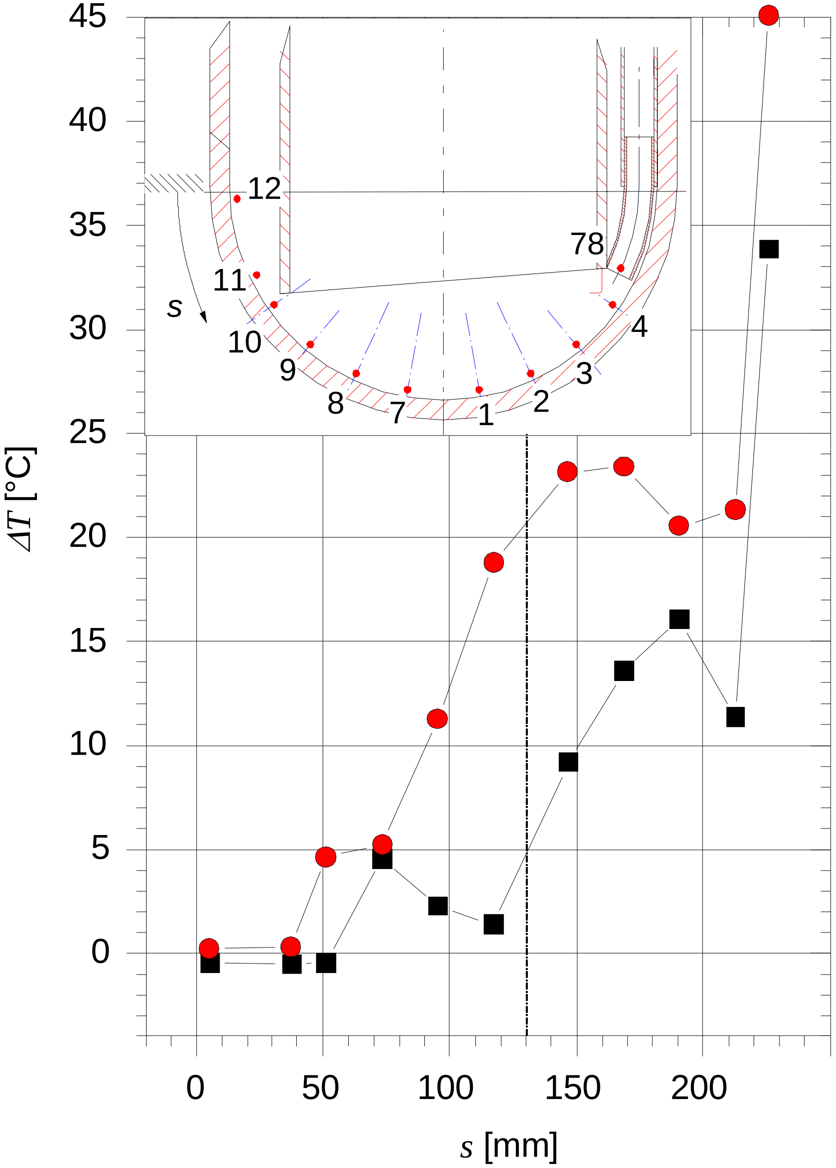
Temperature distribution in the lower shell in nozzle plane (experiment-simulation)

(1) Significant differences already at calc. inlet temperature.

- Experiment different to model (history),
- Inadequate turbulence model.

(2) No double peaks in simulation an jet covering the center line.

- different geometry (differential elongation and change of exp. configuration)
- different velocity distribution (exp.-CFD) because of complex geometry (expressed by non-symmetric *T*-Profiles



Consequence

Detailed analysis of both experimental and CFD data is an **iterative process**

SUMMARY of LIQUID METAL HEAT TRANSFER

Turbulent heat exchange modelling

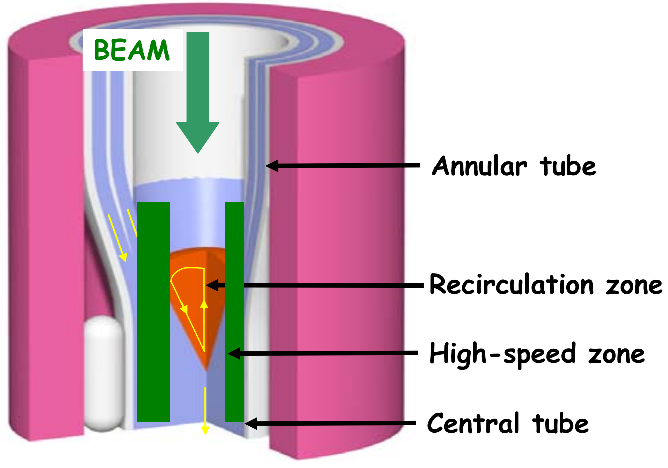
- State of the art Pr_t-correlations in codes!,
- Better buoyant flow modeling (+Qualified user),
- At least ASM based turbulent heat flux models ($u'T'$)
- DNS required to improve and validate advanced heat flux models to be embedded in commercial codes

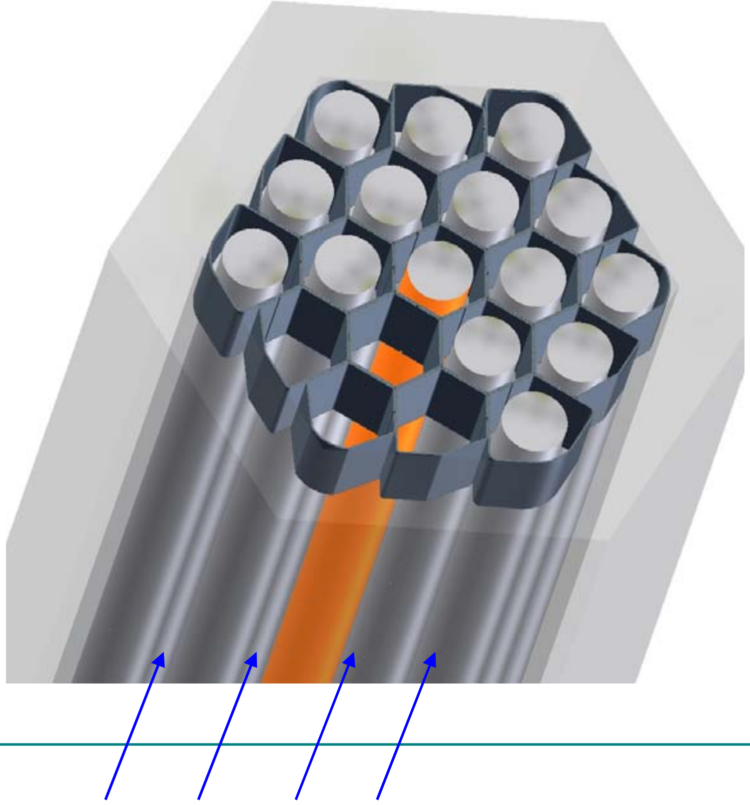
MEASUREMENT TECHNIQUES

- Improved sensors to capture local flow velocities (accuracy, multi-components and spatial and especially temporal resolution, best non-intrusive)
- Defined benchmarks (regarding CFD,LES and DNS but also related to the BC´s with supplementary water experiments)

OUTLOOK at KALLA

- Repetition of heated rod with u', v', $u'T'$, T'^2 and related mean values
  - Accompanying CFD and potentially DNS (ressources)
- Experiments in rod bundles
  - Water experiments with optic means (LDA,LLS,PIV)
  - Liquid metal teat transfer in bundle flows (Local T, T')(mixed, forced and buoyant)
- Free surface target
  - Surface position (stability, meas. technique)
  - CFD modelling (Level-Set, com. codes)





SUPPLEMENTARY FIGURES

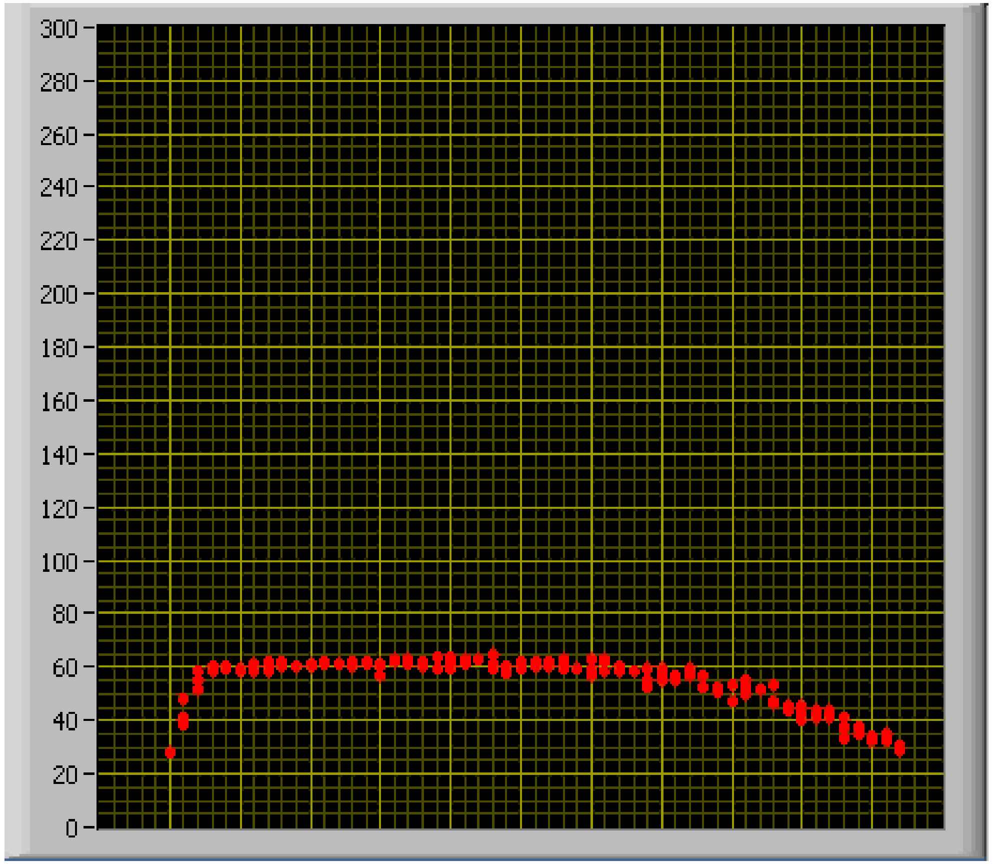
CFD-Calculation strategies for liquid metal flows

Model-Procedure	Momentum	Heat	Time horizon	Comment
Mixed models	*k*-ε-model *k*-Ω-model hybrides (SST) (isotropic)	Reynolds Analogy Pr_t-correlations Pr_t=f(Re,Pr,y^+) +adequate wall functions for T^+	current near	isotropic in all scales WF, mesh,
TMBF model	*k*-ε-model (isotropic)	Transport equations $\overline{u'T'}, \overline{T'^2}, \varepsilon_{T'}$ (still problems with temp. variance dissipation)	near not in comm. codes	performance in conv. purely buoy. flow ? + low *Pe* ?
mixed higher order	kubic *k*-ε-model ASM RSM	Transport equations $\overline{u'T'}, \overline{T'^2}, \varepsilon_{T'}$ (Constants fort ransport eq. from DNS)	req. scientific benchmark	promising results (lacking exp. data)
Exact solution	DNS	DNS	future benchmark	

⬜	0th order direct coupling	🟩	2nd order Tensorial GDH
🟨	1st order Gradient diffusion hypotesis	🟥	exact solutions

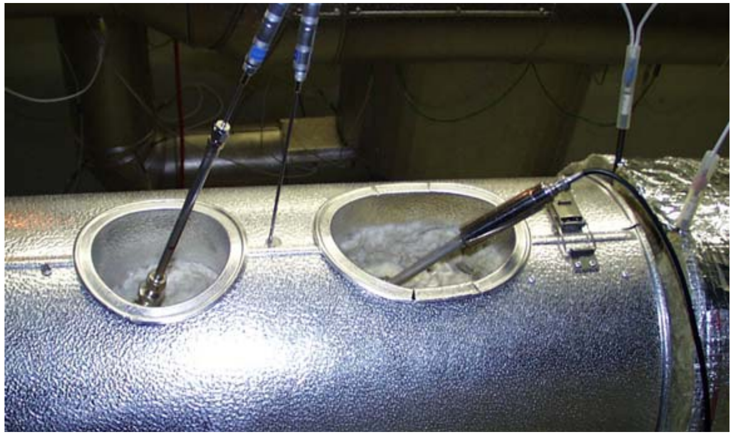
- Model coefficients depend also (!) on *Re*, *Pr*, geometry
- Similar classification for LES

Velocity :Ultra-Sound Doppler Velocimeter (UDV)

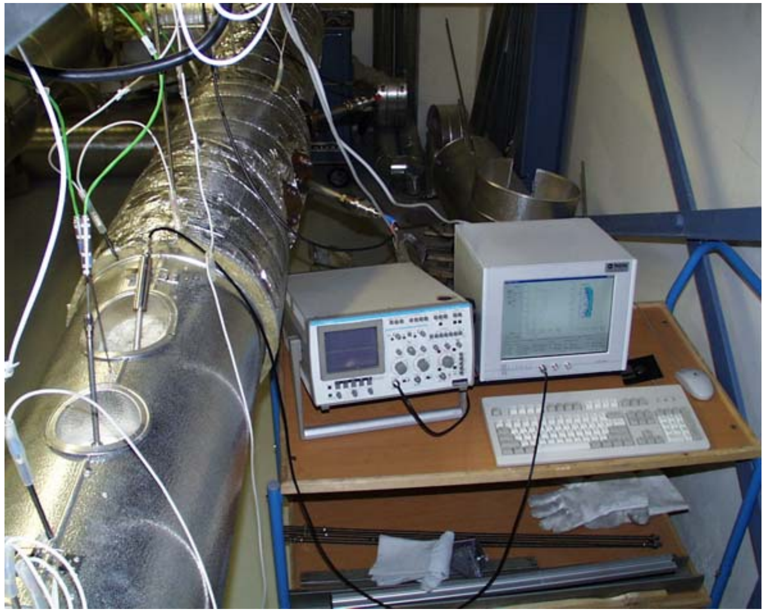


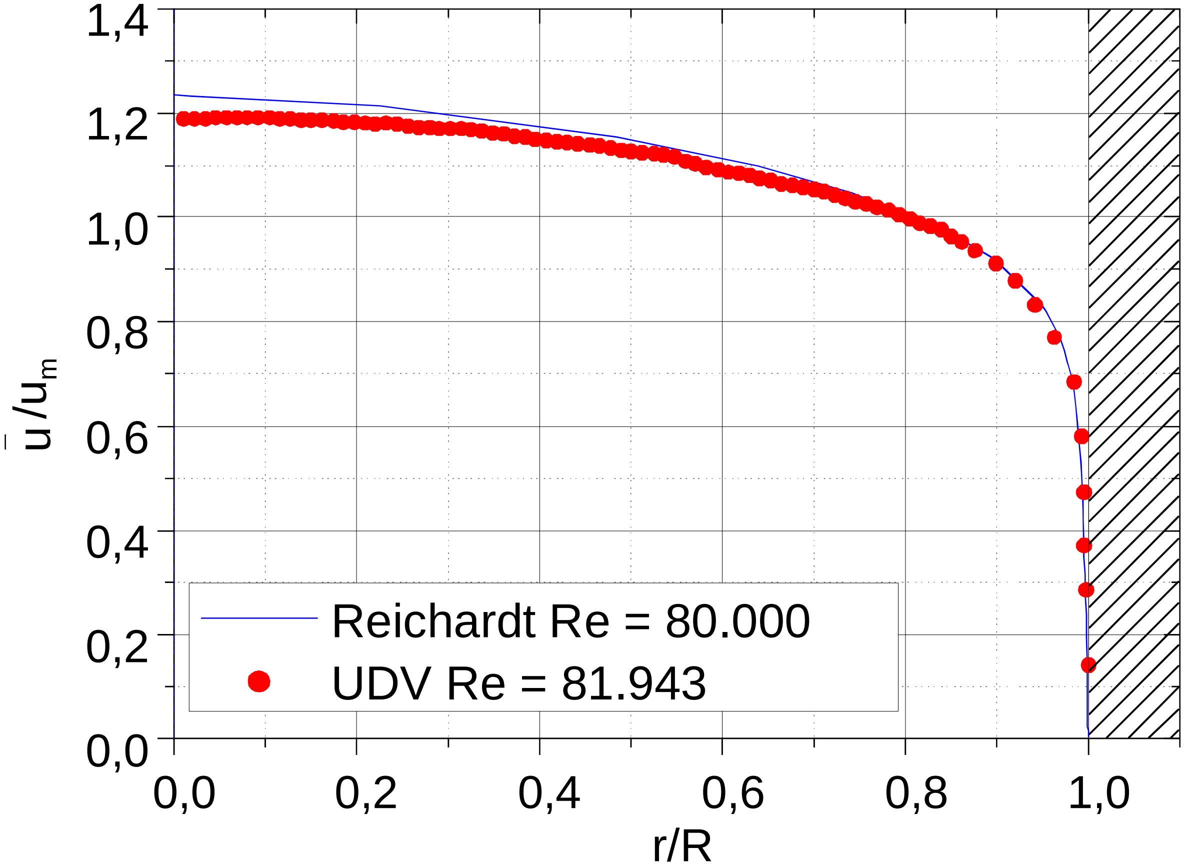
Transient start-up behaviour of
EM pump in THESYS Loop

- Fluid temperature: 400°C
- Temperatur compensation durch (Wave Guide)
- Inclination angle: 45°
- Tube diameter: 60 mm



Velocity: Ultra-Sound Doppler Velocimeter (UDV)

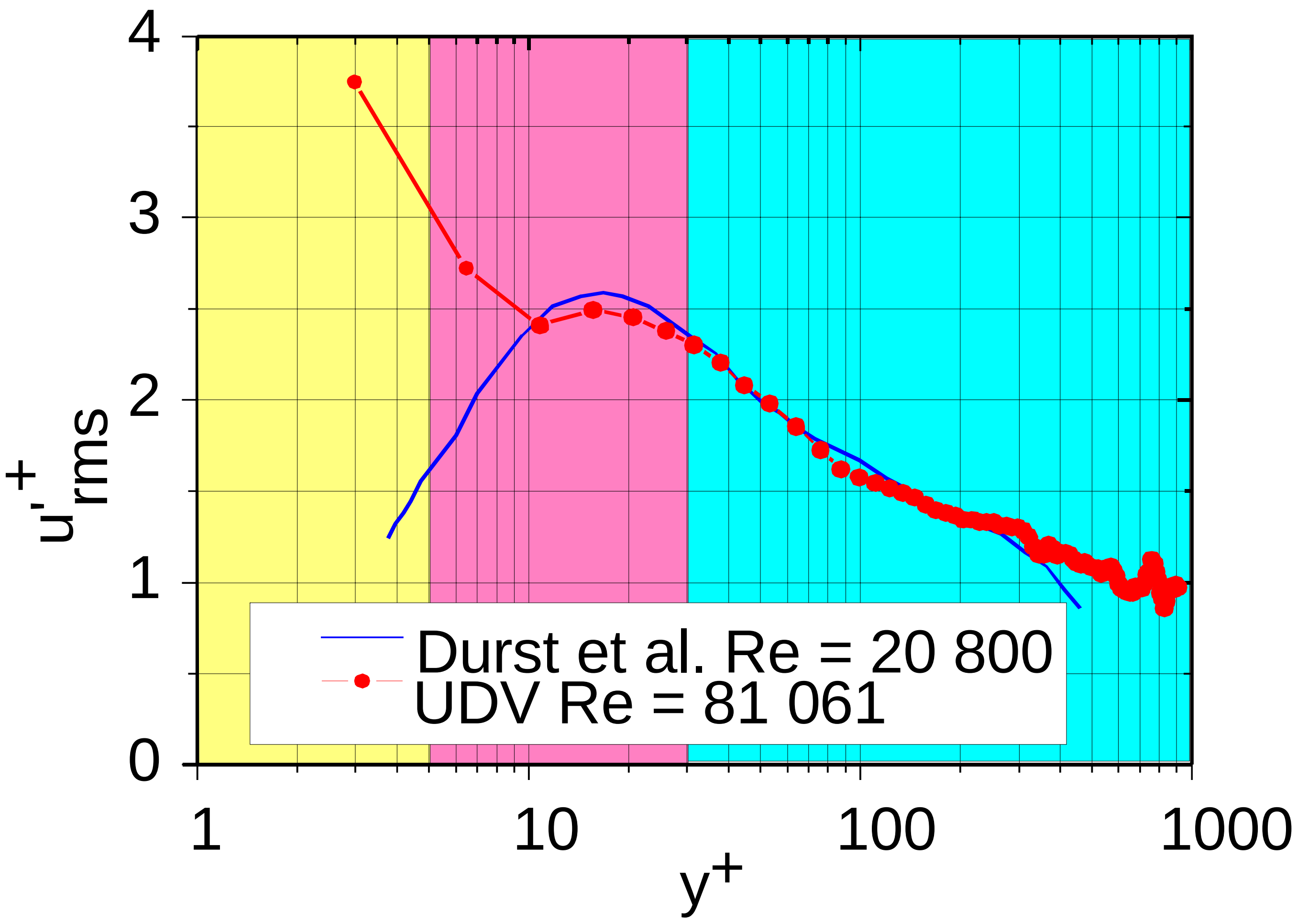




- Excellent agreement between measurement and literature profile
- Detailed resolution of the velocity profile
- Deviation from literature profile for r/R>0.6 less than 0.5%

PhD Thesis C.-H. Lefhalm 2004

UDV Fluctuation measurements in boundary layer in a tube



Supporting Water experiments

HYTAS

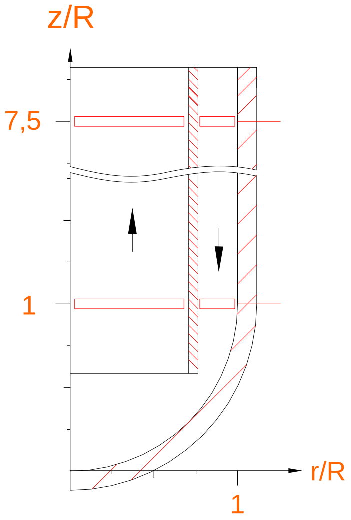
$Re_{inflow,gap} = 60.000$

$Q_{main} / Q_{bypass} = 15 / 1$

Simulation of the momentum exchange in MEGAPIE

- Optimization of the nozzle (Geometry,Location).
- Determination of best operation point ratio of main to jet flow rate.
- Verification of CFD simulation for momentum transport

→ Experiments in transparent media at the same Reynolds- numbers using optic methods (LDA,LLS,UDV)



Batta, Grötzbach, 2003, Jahrestagung Kerntechnik(Numerik), Eiselt 2003 (FZKA-6618)

Axial Velocity Profile down the riser pipe at ϕ=0°

Experimental Set-UP

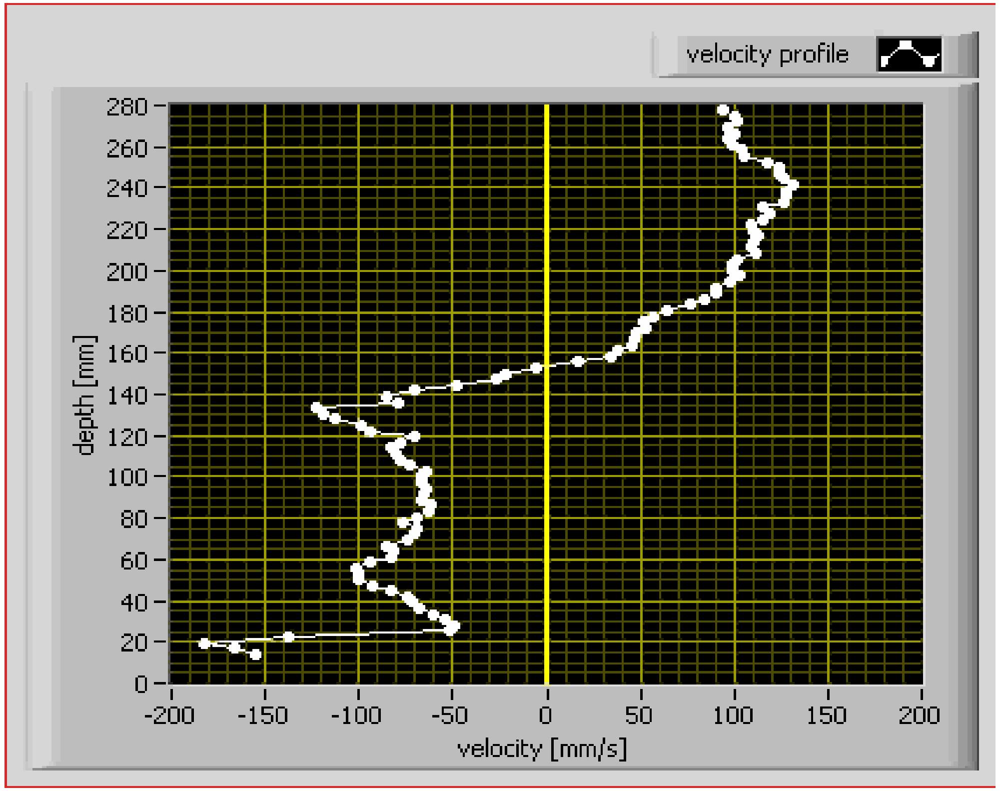
- UDV technique
- 4MHz sensor parallel to the riser pipe at ϕ=0°(r/R=0.66)
- Re=5.2·10^4

Observation

- Highly turbulent flow
- Oscillation of the stagation point along the riser tube.
- Time dependent two stagnation points appear.

RESULT

- Strong time dependence (LES started)



OUTLOOK- LIQUID METAL FLOWS

- So far only single phase heat transfer considered.
- But, advanced technical concepts in nuclear community and industrial processes involve new physical aspects, which are of challenging character, such as
  - Free surface flows
  - Two-phase flows
  - Freezing/remelting