Heavy liquid metal modelling activities
and
CFD applications

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Related Technology (HeLiMeRT 2009)
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Introduction

HLM Related studies in flow modeling group at IKET

ASSESSING ONGOING EXPERIMENT

- **Rod Bundle Experiments**
- **Heated rod experiment**
- **FREE SURFACE ANALISYS OF XTADS TARGET WATER EXPERIMENT**

Fundamental studies and model development

- **Liquid Metal Forced convection over a Vertical Backward Facing Step**
- **Circular HYDRAULIC JUMP**
- **1D THERMOHYDRAULIC ANALYSIS**

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Liquid metal cooled reactors

- **Motivation**

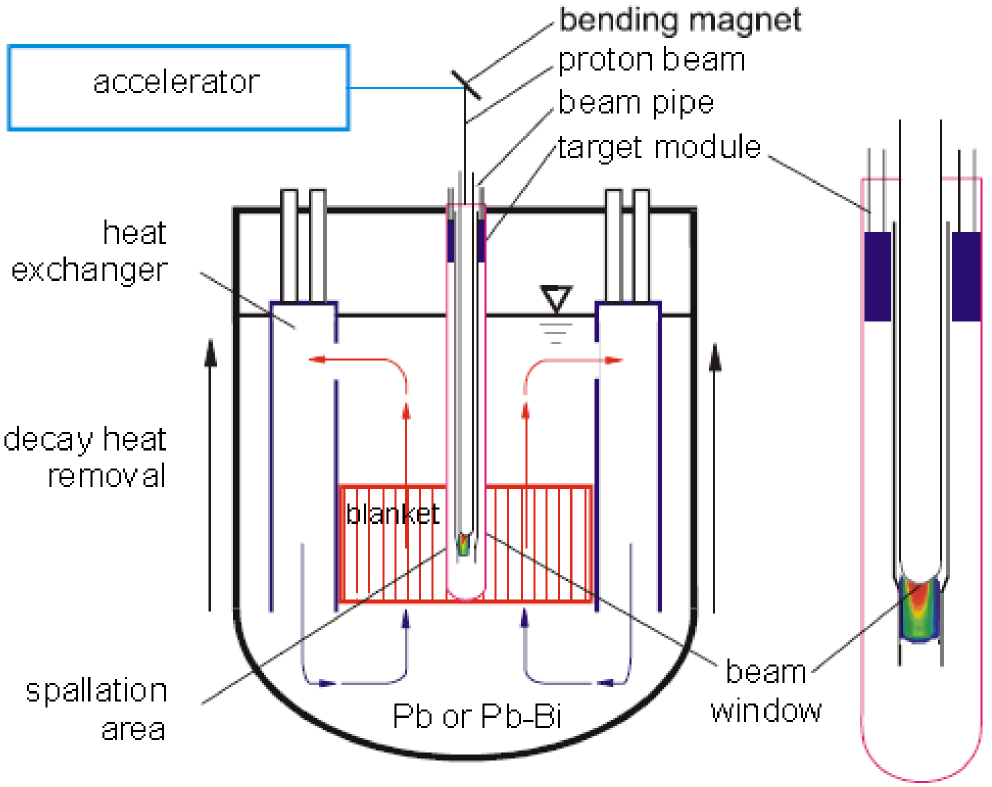
  Minimization of Radio-toxicity of long lived fission products(Am,Cu,Np,..)

- **Realization options**

  - Accelerator Driven Systems
  - Fast critical reactors

- **Open issues**

  -Turbulent liquid heat transfer along fuel pins and bundles



Sketch of ADS

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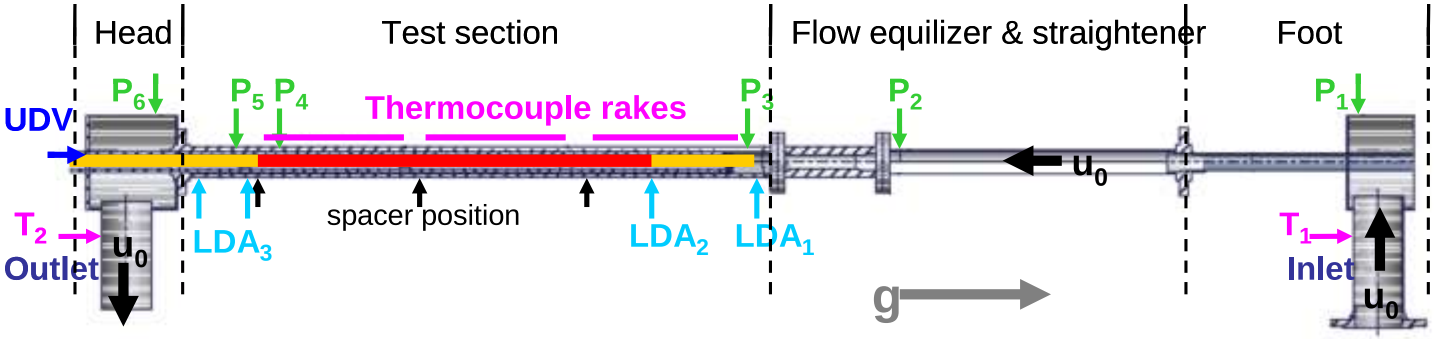
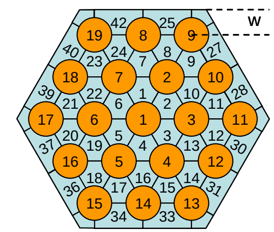
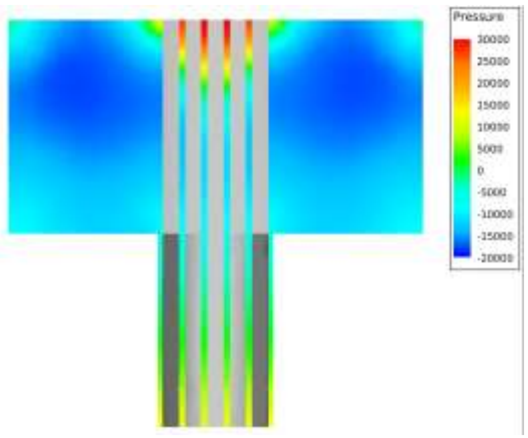
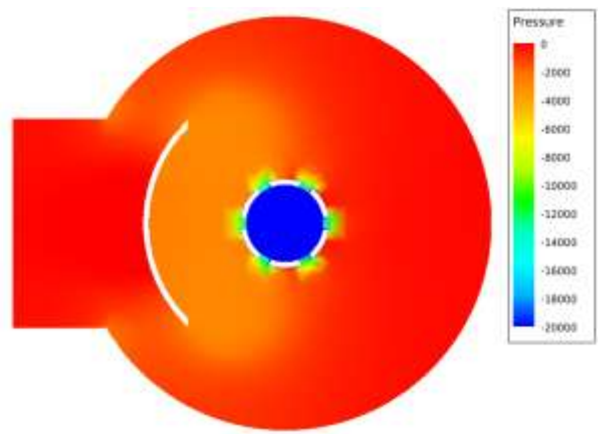
Rod bundle experiment







Outlet plenum (Head), optimized length



Optimized inlet plenum (Foot)

Results: outlet length is optimized so that the stagnation pressure does not penetrate in the bundle

CFD optimized inlet plenum ensures nearly uniform inlet conditions

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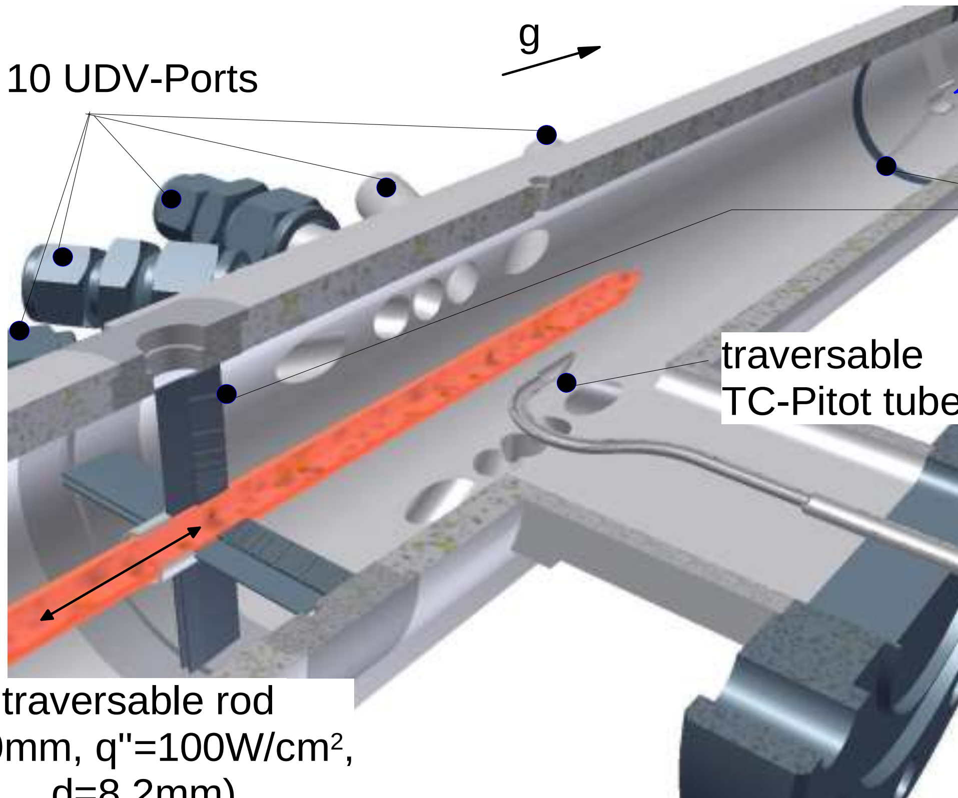
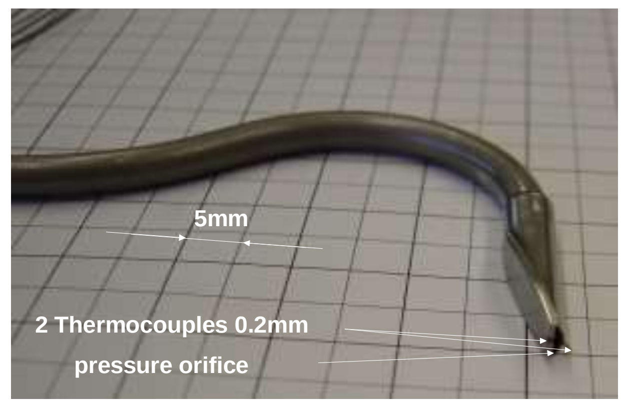
Single Rod Experiment

- Turb. heat transfer in forced, mixed and buoyant convec. flows ($Re \rightarrow 6 \cdot 10^5$)
- Aim:
  - Development of models for turbulent heat flux
  - Determination of Nu-correlations
  - Evaluation of transition regimes (forced→mixed → buoyant)
  - Assessment of applicable CFD turbulence models and their validity)



3 Rakes (60 TC´s, d=0.25mm)



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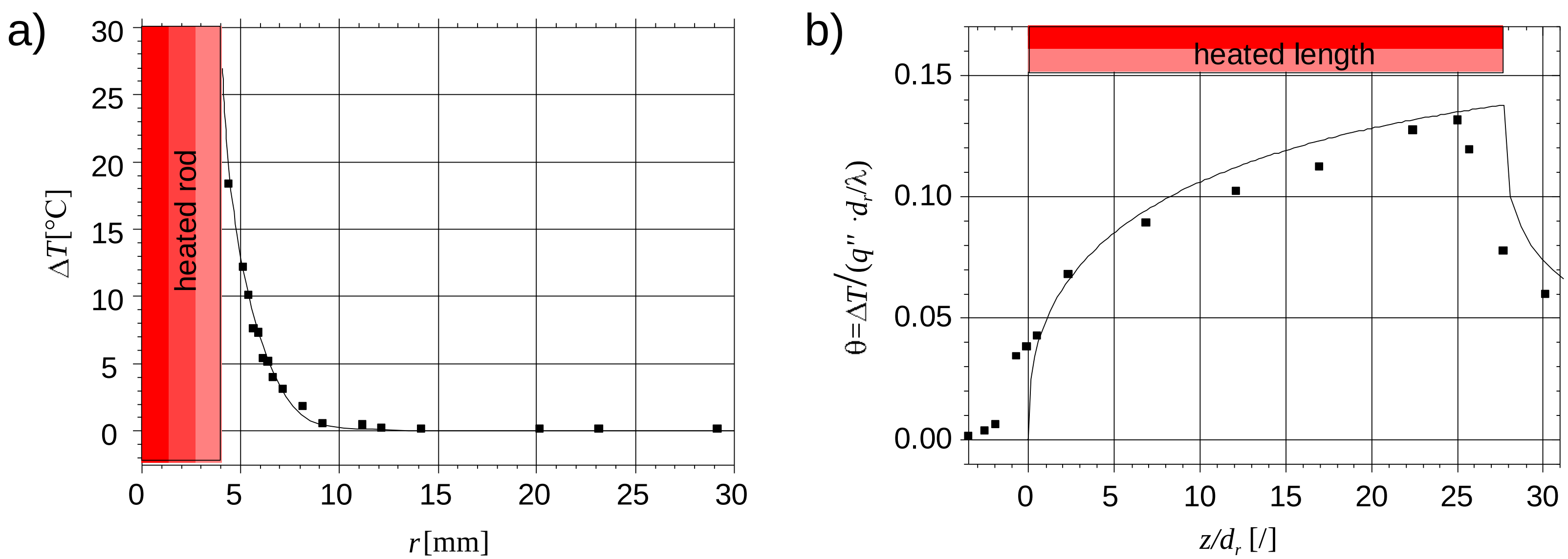
Validation of numerical methods, short heated rod

a.) Meas. and calculated mean radial temperature profile at z/d_r=22.6.
b.) Meas. and calc. dim.-less axial fluid-wall interface temperature. Both for *Pr*=0.022 and Re=2.67.105.



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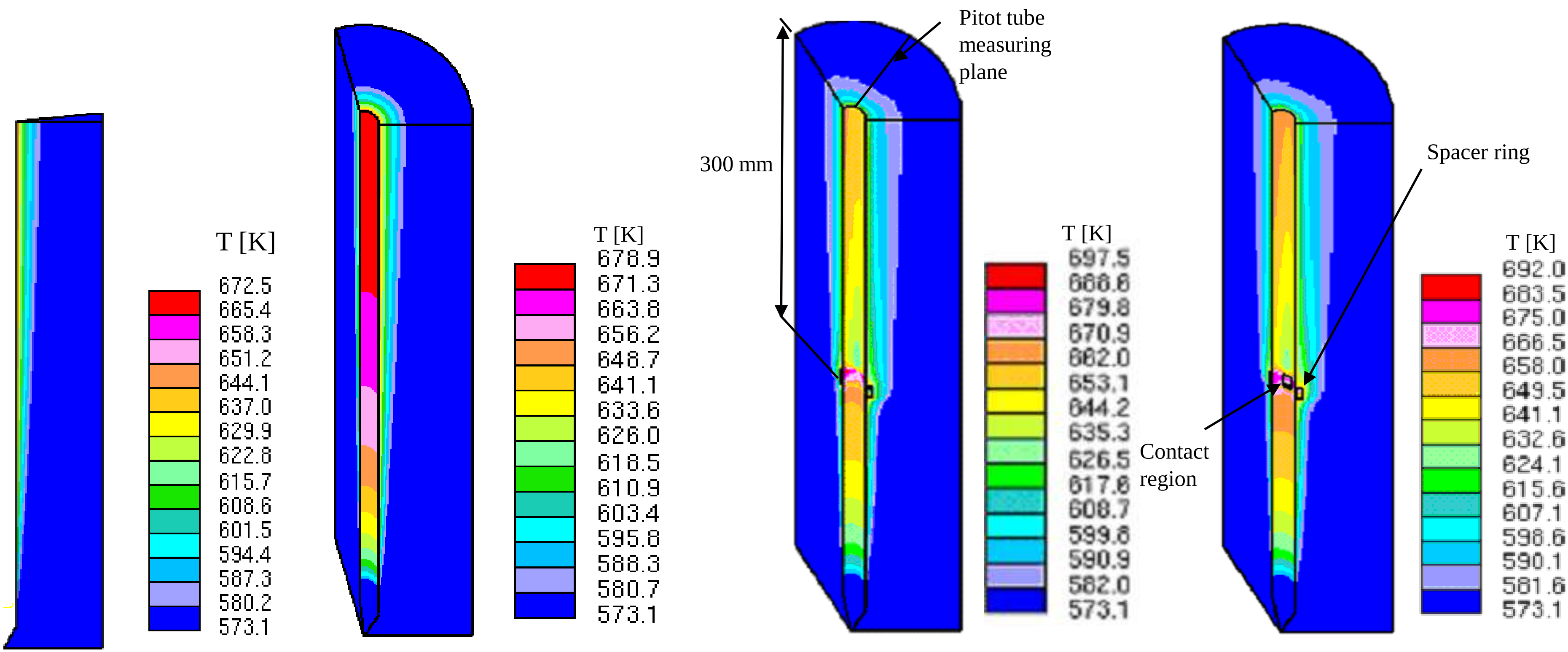
Temperature contours due different tested cases



a) Axis-symmetry, developing flow length of 1.223 m

b) No spacer, axis-symmetry

c) Spacer has no contact with rod

d) Spacer in contact with the rod

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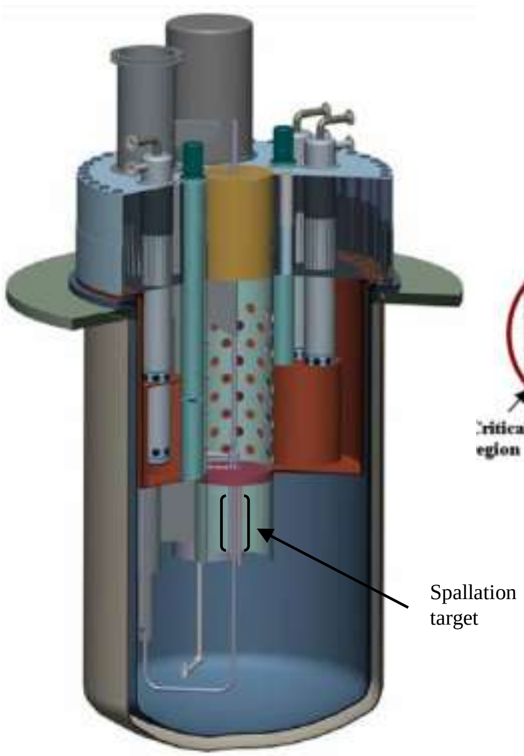
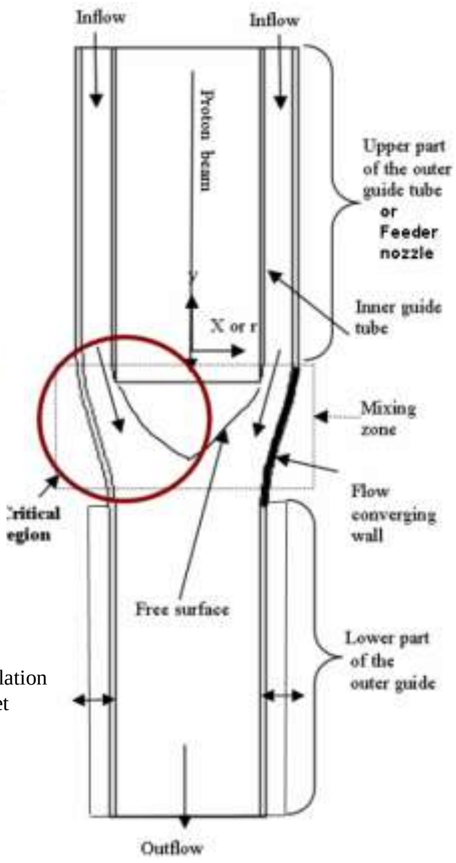
XT-ADS target design





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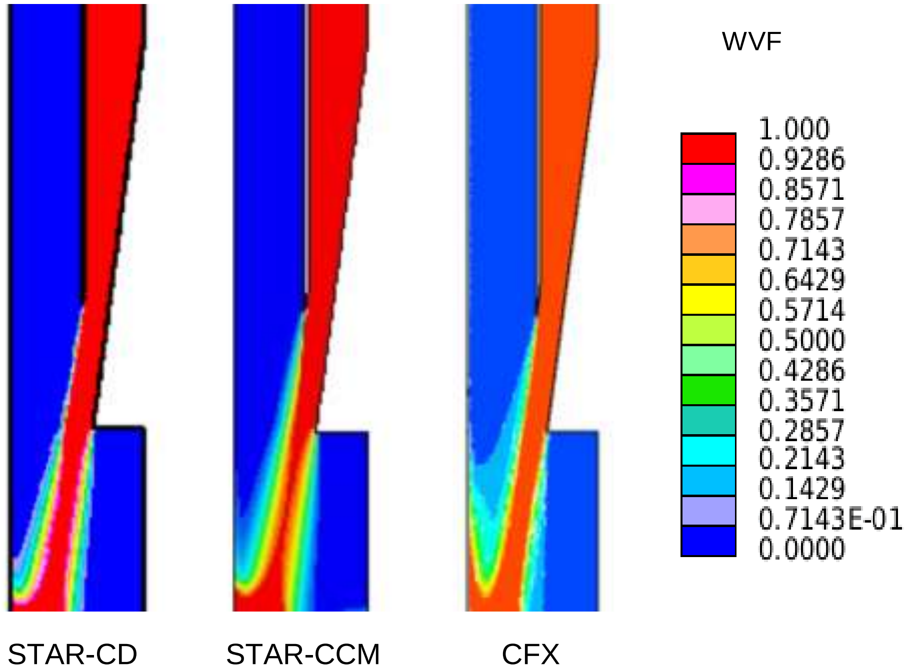
Final Design for XT-ADS Water experiment

Water volume fraction results obtained from STAR-CD, STAR-CCM and CFX codes for nominal flow, 10 l/s, 0 denotes water and 1 denotes vapor



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Heat Flux Modelling

- Turbulent energy equation

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

- 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)

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

- Typical problems (CFD Simulation with standard value 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)
  - Unphysical in case of non-hydraulically developed flows
  - Heat flux opposite to T-Gradient possible (?)

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Heat Flux Modelling

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Model order	Momentum field Isotropic turbulent transport	Energy field Anisotropic turbulent transport	Number of transport equations
1st	Gradient models, eddy conductivity models		0
	Pr_t- Reynolds analogy		0
	l_{hy} mixing length models	l_{th} mixing length models	0
	k-ε-T'^2, k-ε-T'^2- $\varepsilon_{T'}$		2+1, 2
	Non-linear Algebraic heat flux models		2+2
?		(AHM)with T'^2	1,2
2nd	Transport equations for all 2nd order closure moments		
		Equations for complete heat flux vector	3+1,2

- Commercial Fluid Dynamic codes (yellow)
- Scientific codes (TMBF; TRIO-U; Turbit) (cyan)

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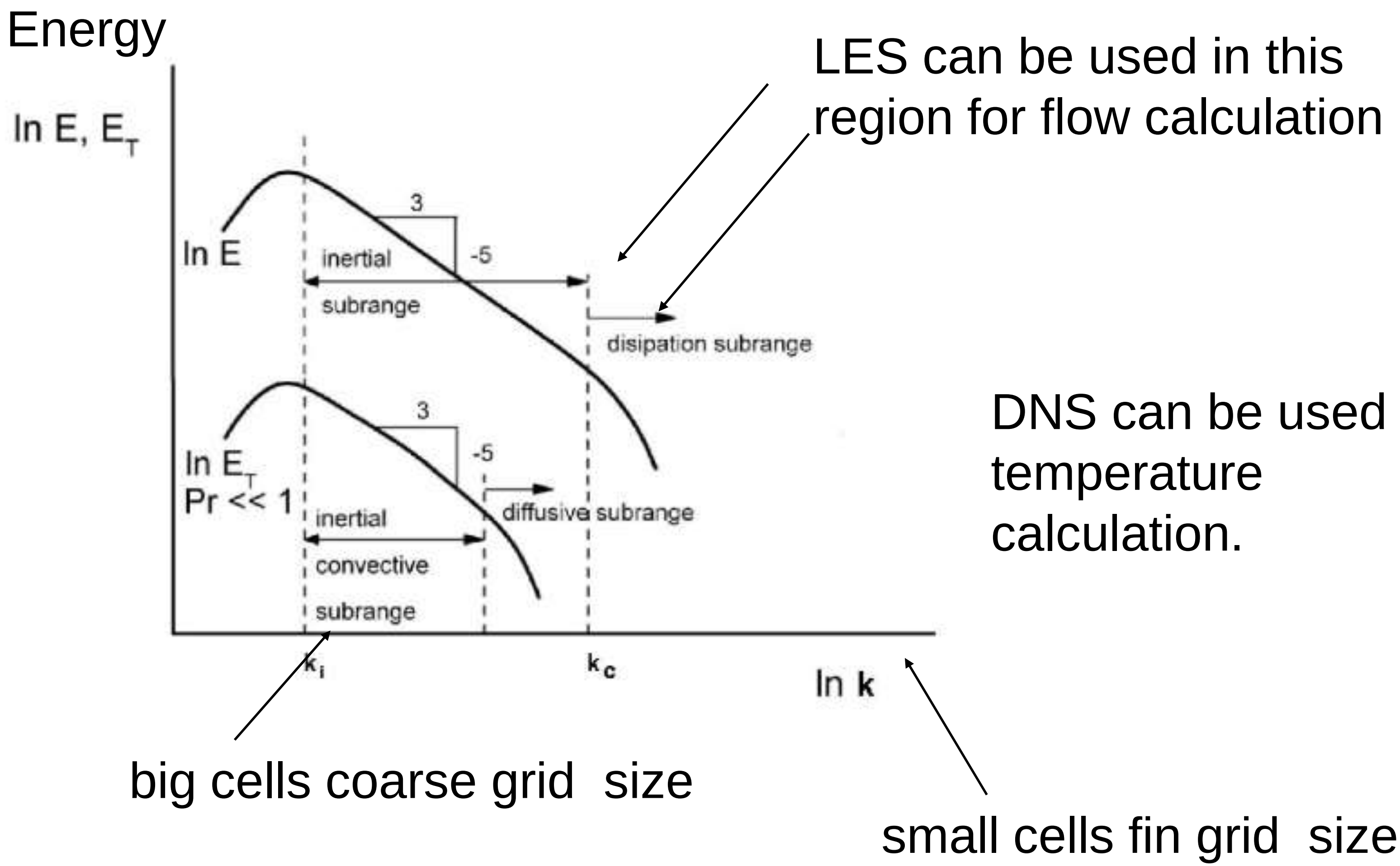
Fundamental study for turbulent flow calculation

Liquid Metal Forced convection over a Vertical Backward Facing Step



DNS can be used for temperature calculation.

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Example of application,

Numerical Investigation of Turbulent Low-Prandtl-Number Forced Convection Over a Vertical Backward-Facing Step

Re_{Li}=10 000

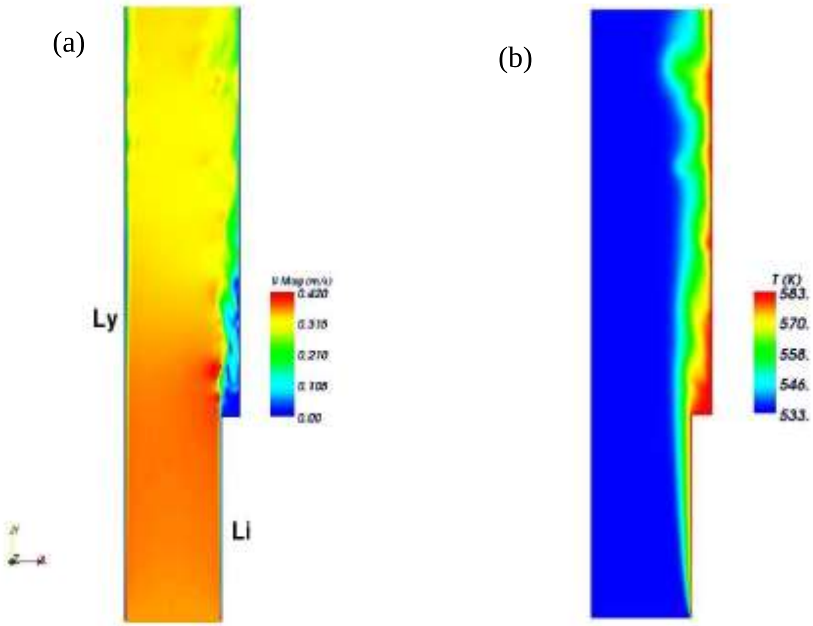
Pr=0.006

Grid 70X60X20

$Ly = 30h$

$Lx = Lz = 6h$

$Li = 10h$



Velocity turbulence are not reflected in the temperature field due to large thermal diffusivity of sodium.

Visualization of the instantaneous fields at the same time: (a) velocity (b) temperature. The difference between the fields is due to the low molecular Prandtl number.

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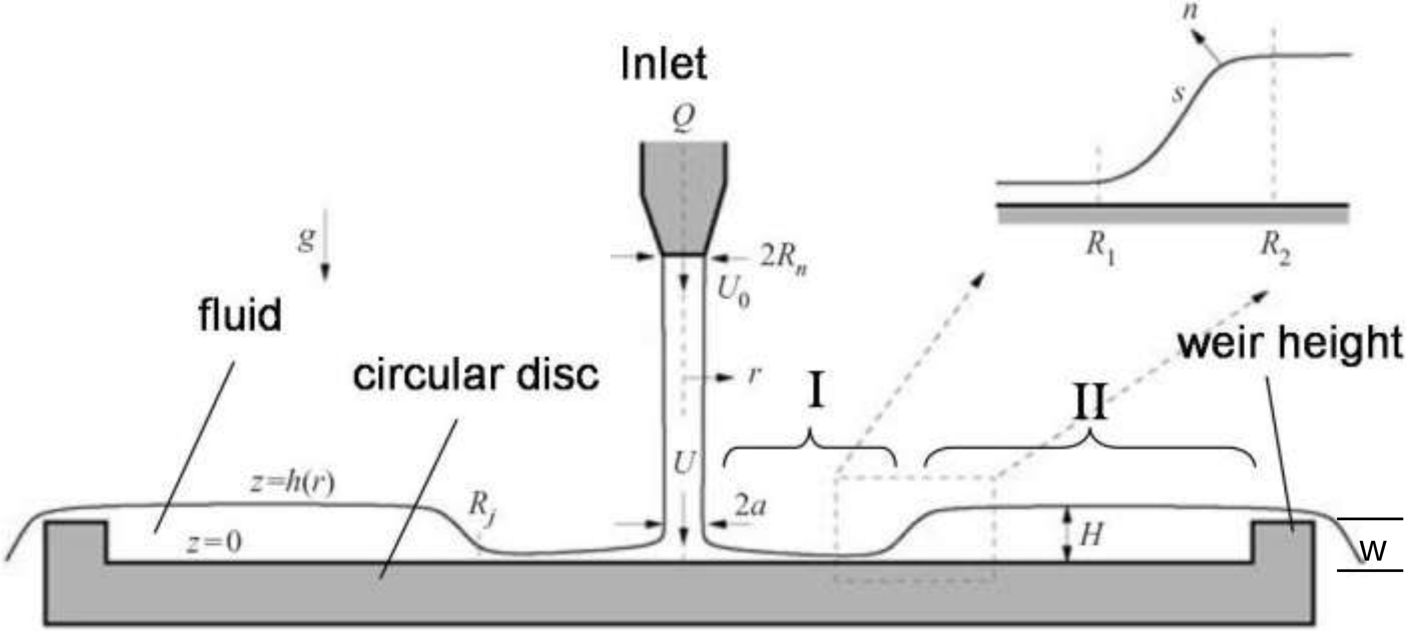
Hydraulic Jump

(Bush, Aristoff 2003)



Hydraulic Jump

- transition between supercritical (Fr>>1) and subcritical (Fr<1) flow

Froudenumber $$Fr = \frac{u}{\sqrt{g \cdot l}}$$

- discontinuous
- jumpposition based on equilibrium of forces
- rotationalsymmetric

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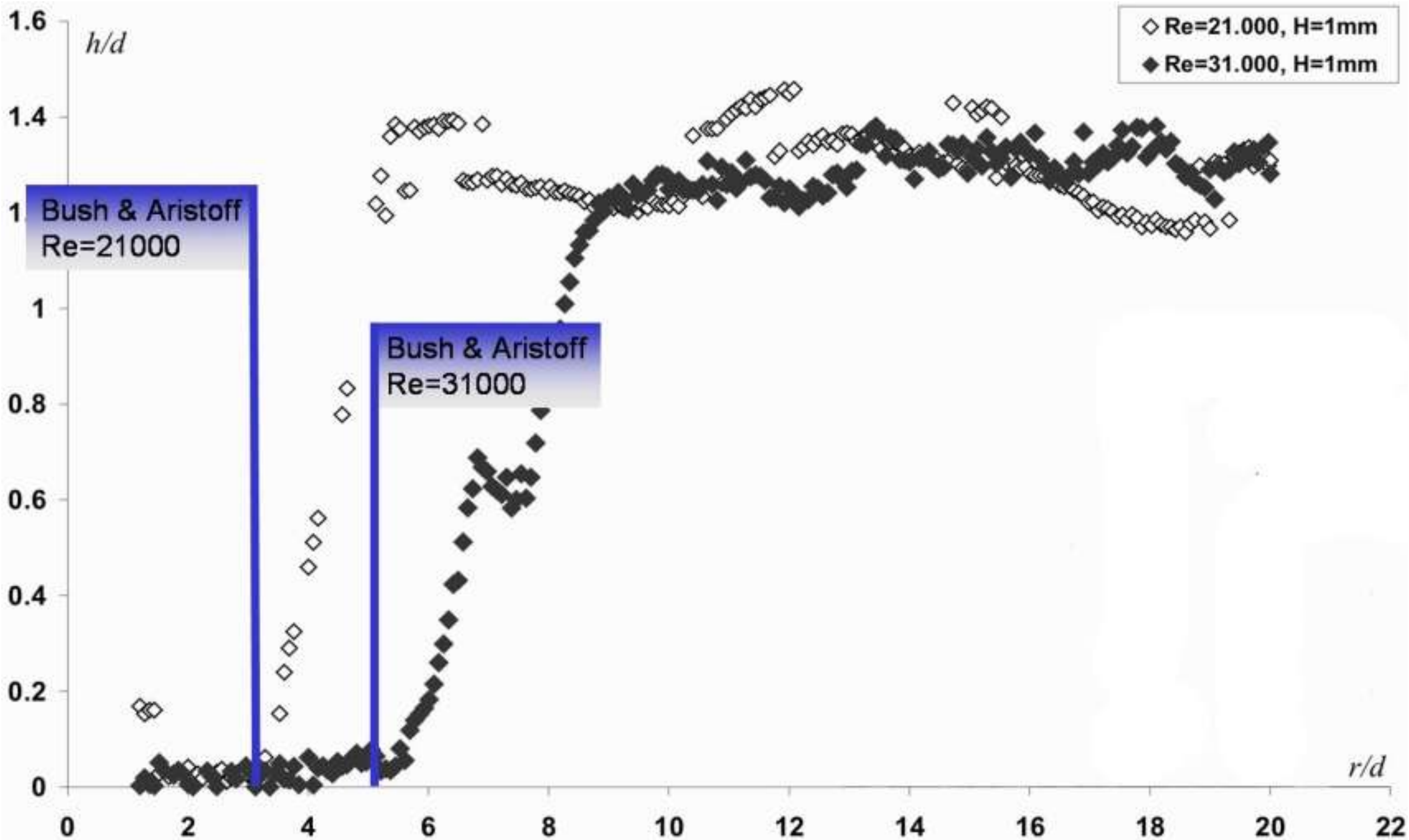
Experiment-Theory



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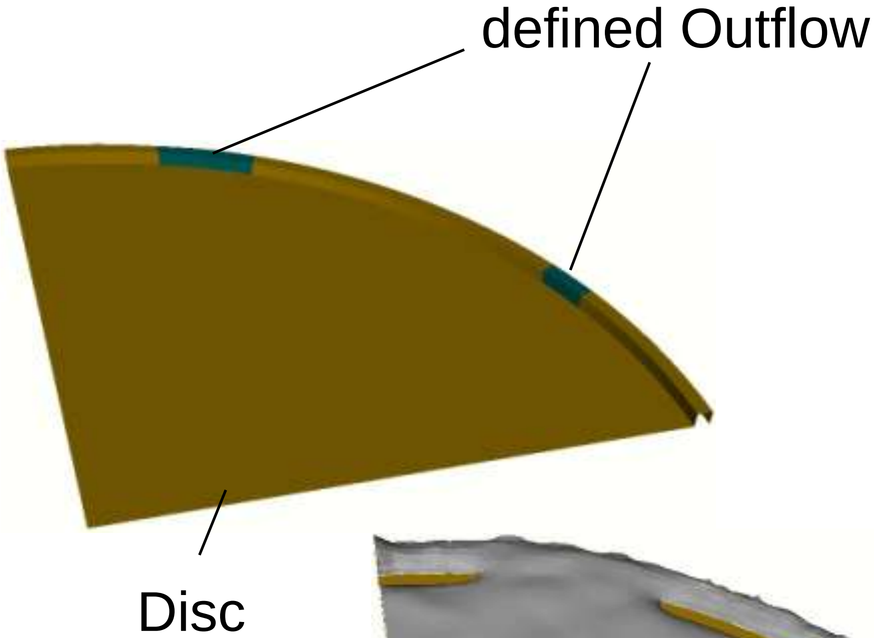
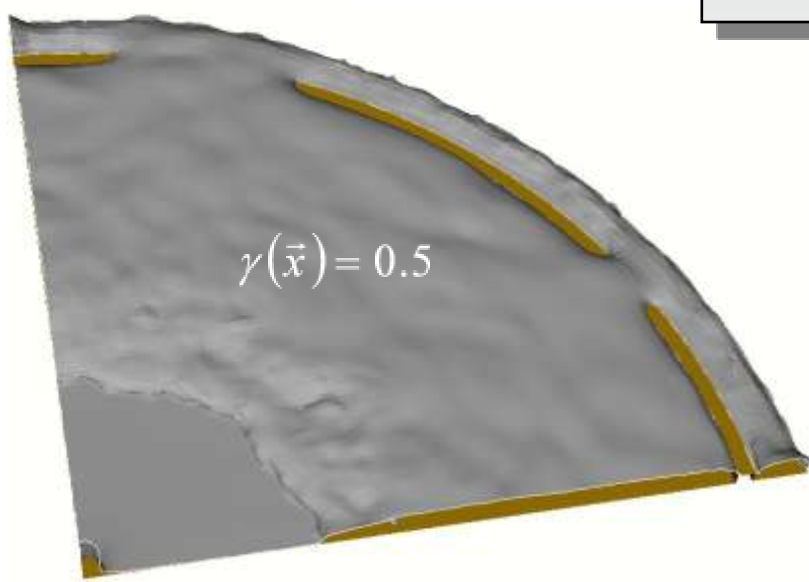
Hydraulic jump





defined outflow

- no fluctuations at the weir
- outflow width 2mm and 1mm
- better comparibility experiment - numerics

Making use of experimental and numerical results analytical description of the jump for HLM is being prepared

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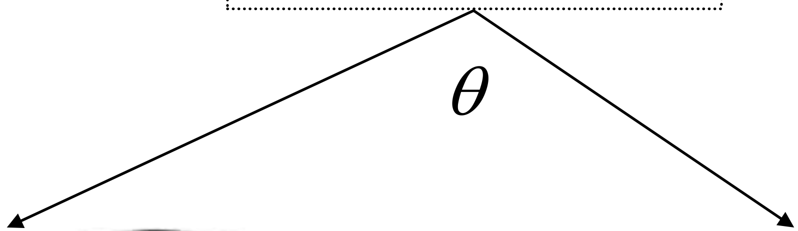
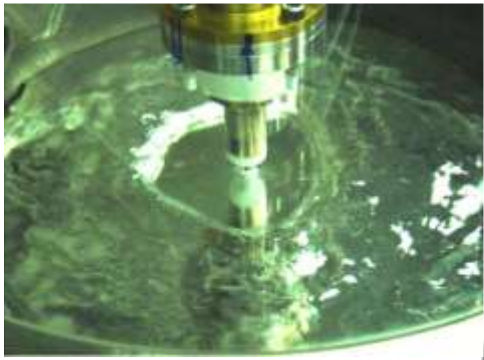
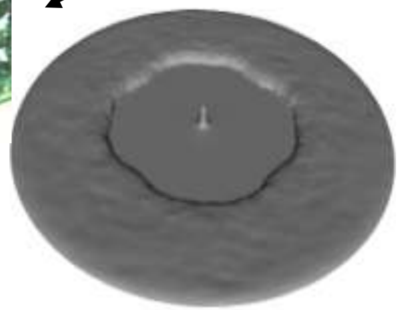
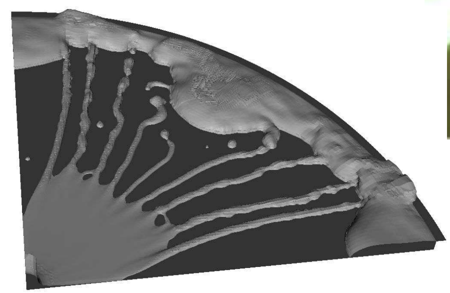
Hydraulic jump

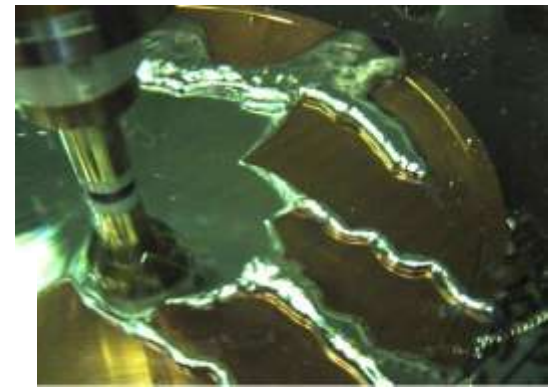
Gallium indium tin
$Ga68In20Sn12$
$\rho = 6363.2\ kg/m^3$
$\sigma = 0.532\ N/m$











Experiment shows two distinct flow configurations at identical flow rates

- left wetted surface
- Right partially wetted surface

Only difference is that before the experiment
on the right the surface was cleaned with an oilly cloth

In nuclear applications fingering must be omited

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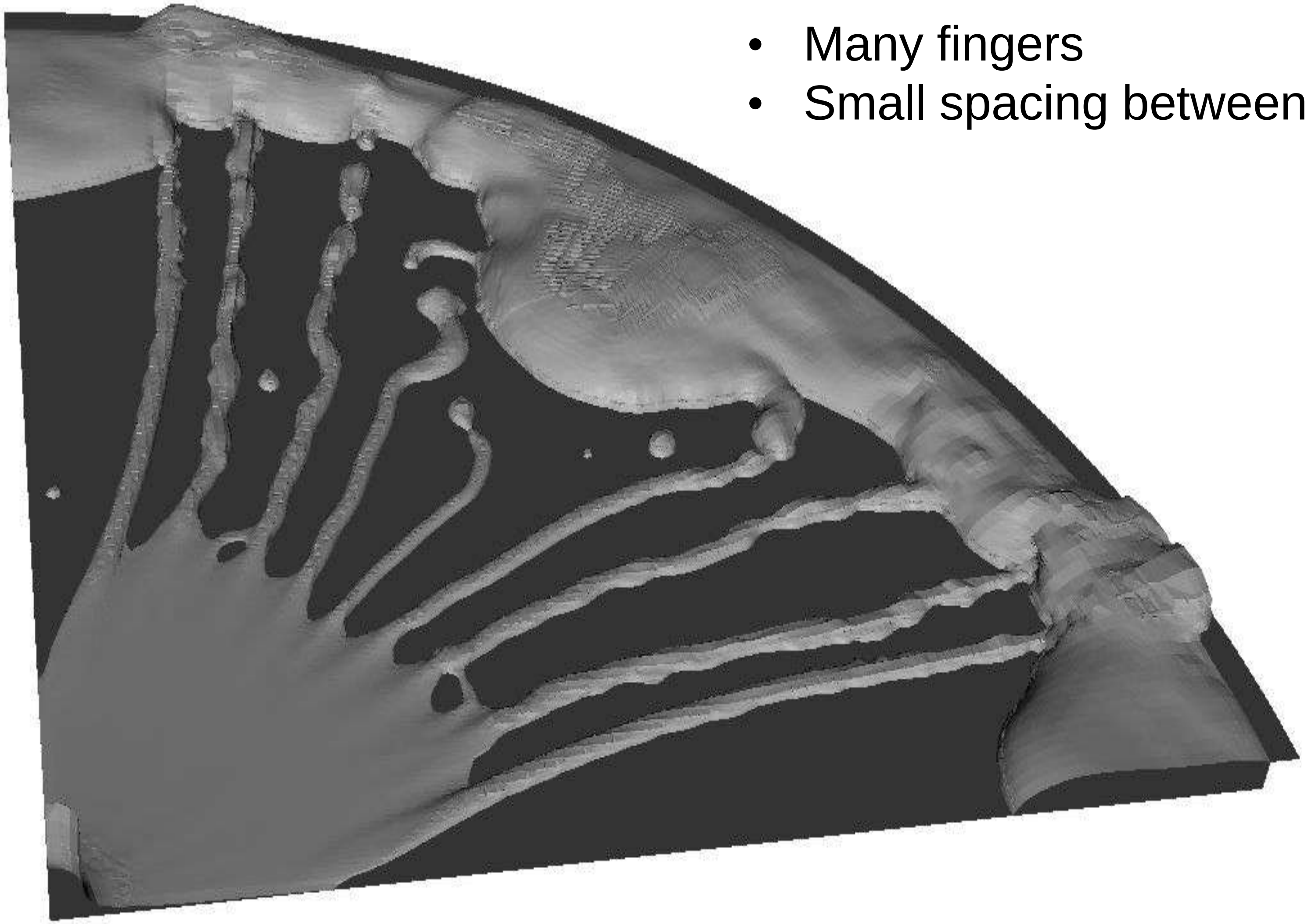
VoF Simulation $\theta=\pi/2$



- Many fingers
- Small spacing between fingers

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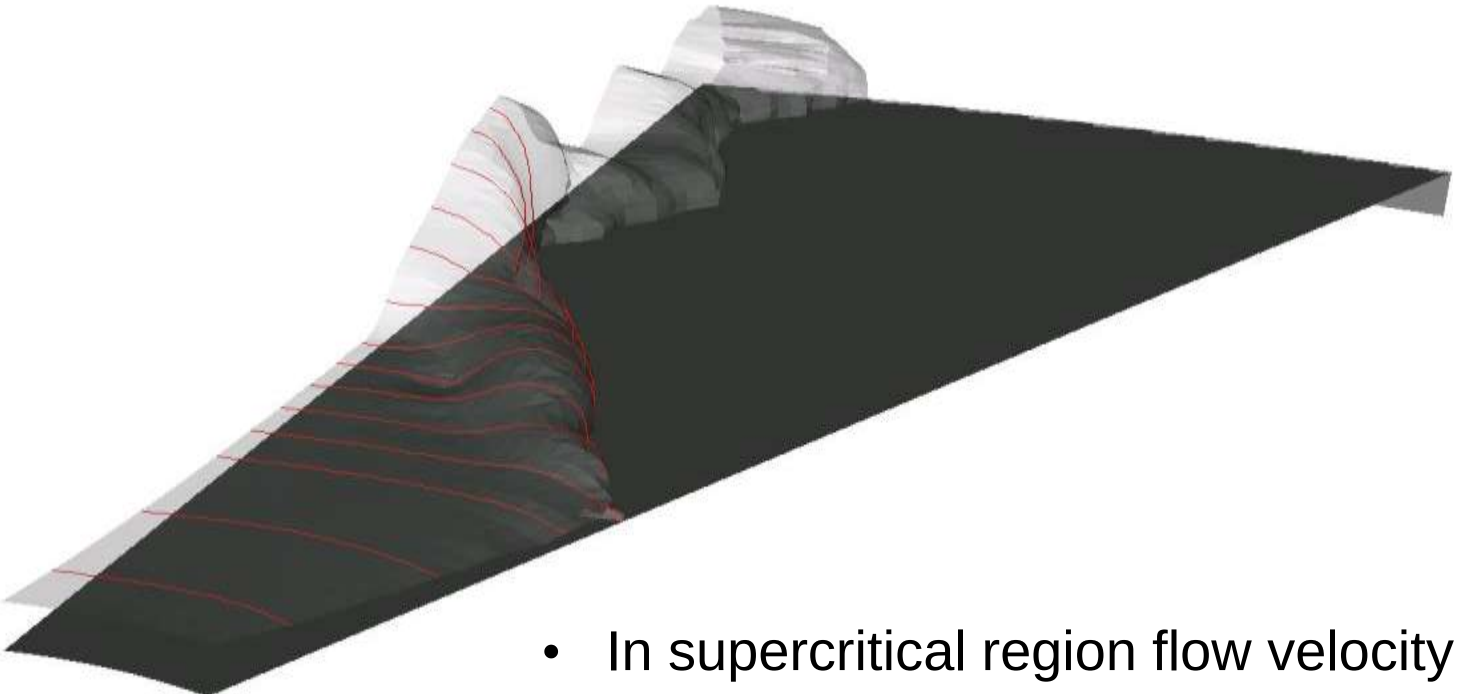

- In supercritical region flow velocity is constant and layer thickness shrinks with radius
- Transition region has triangular shape with constant layer thickness on centerline
- Unsteady surface waves on finger

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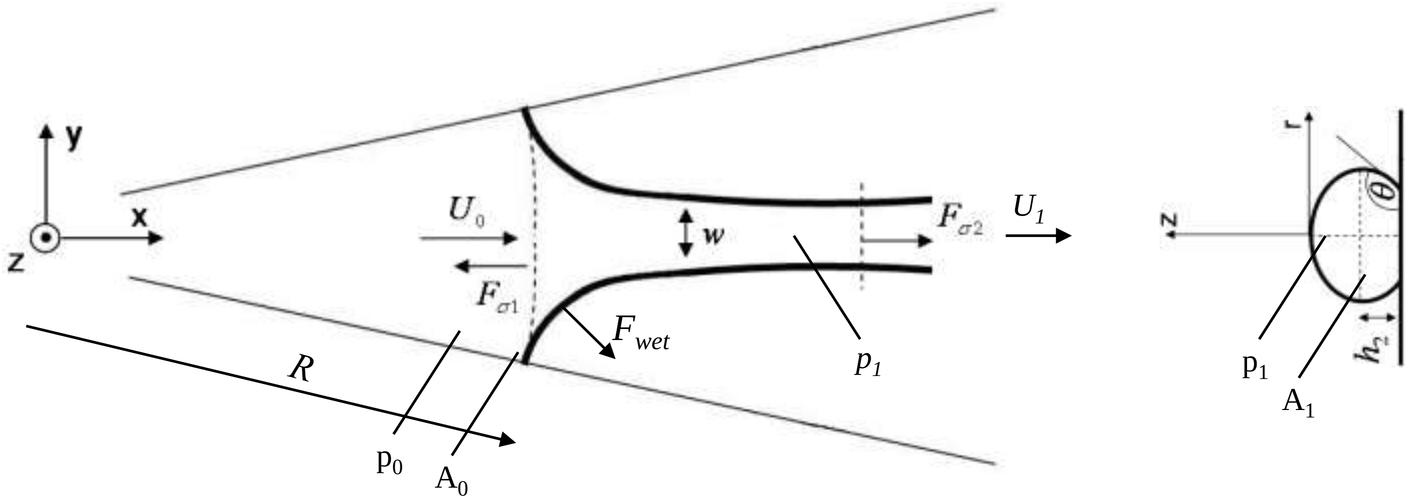
Mathematical model



Continuity: $$U_0 A_0 = U_1 A_1$$

Bernoulli: $$U_0^2 (1 - \xi) + p_0 = U_1^2 + p_1$$

Forces; $$F_{\sigma_2} - F_{\sigma_1} + U_0^2 A_0 - U_1^2 A_1 - p_1 + F_{wet} = 0$$

$$F_{\sigma_1} = R \cos\alpha, \qquad F_{\sigma_2} = l_{arc}$$

$$F_{wet} = (R \cos\alpha - w) \cos\theta$$

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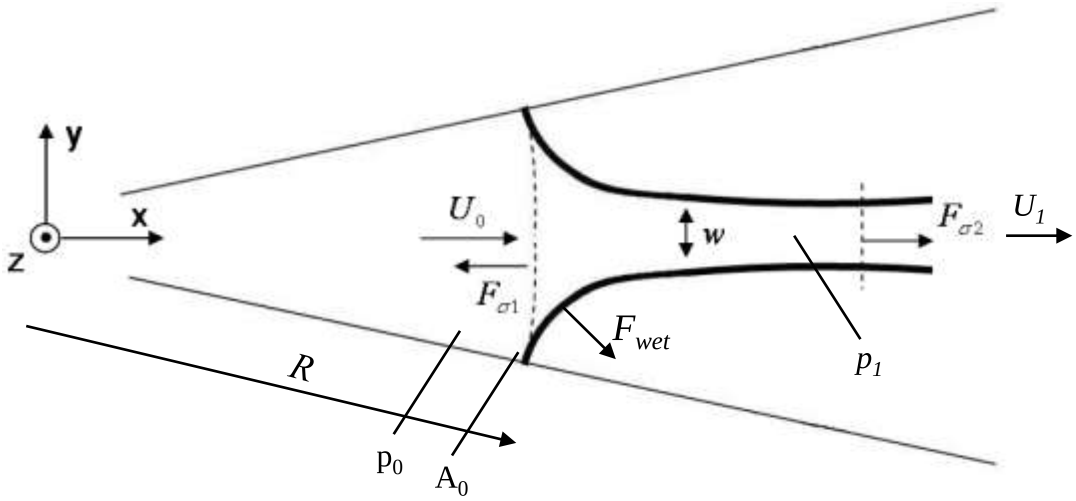
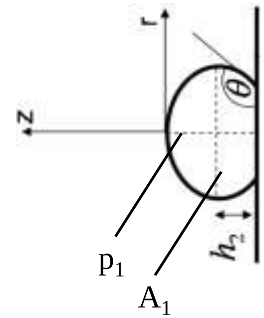
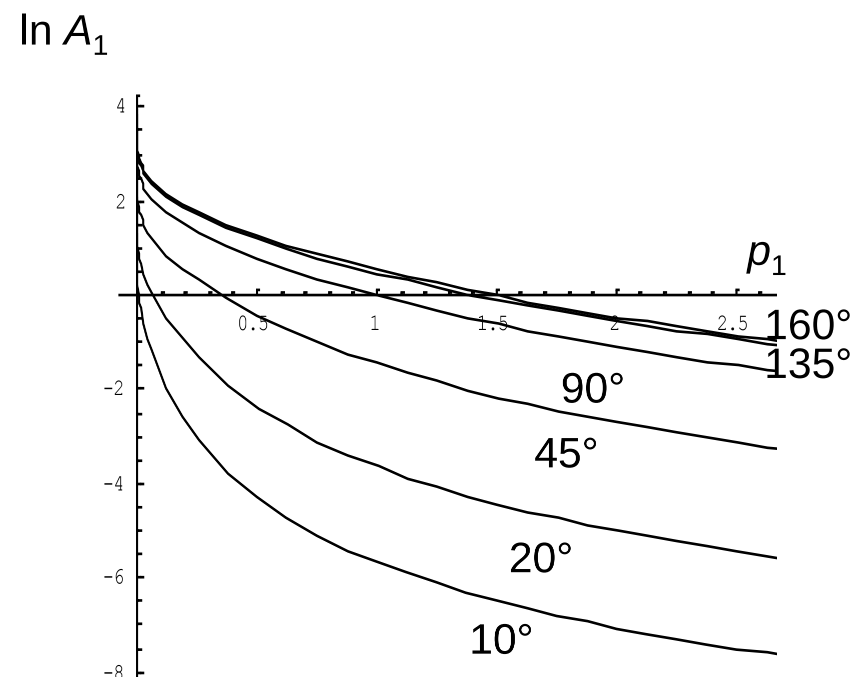
Mathematical model







Young-Laplace-Equation:

$$z + p_1 = -\frac{d}{dz}\frac{y'(z)}{\left(1+y'(z)^2\right)^{1/2}} \quad \Rightarrow \quad y'(z)$$

$$h_1 = -p_1 + \sqrt{p_1^2 + 2\left(1-\cos\theta\right)}$$

$$A_1 = \iint_{A_1} \nabla \bullet \left(0, z\right) dA = 2\int_0^{h_1} \left(h_1 - z\right) y'(z)\, dz$$

$$w = 2\int_0^{h_1} y'(z)\, dz \qquad l_{arc} = 2\int_0^{h_1} \left(1+y'(z)^2\right)^{1/2} dz$$

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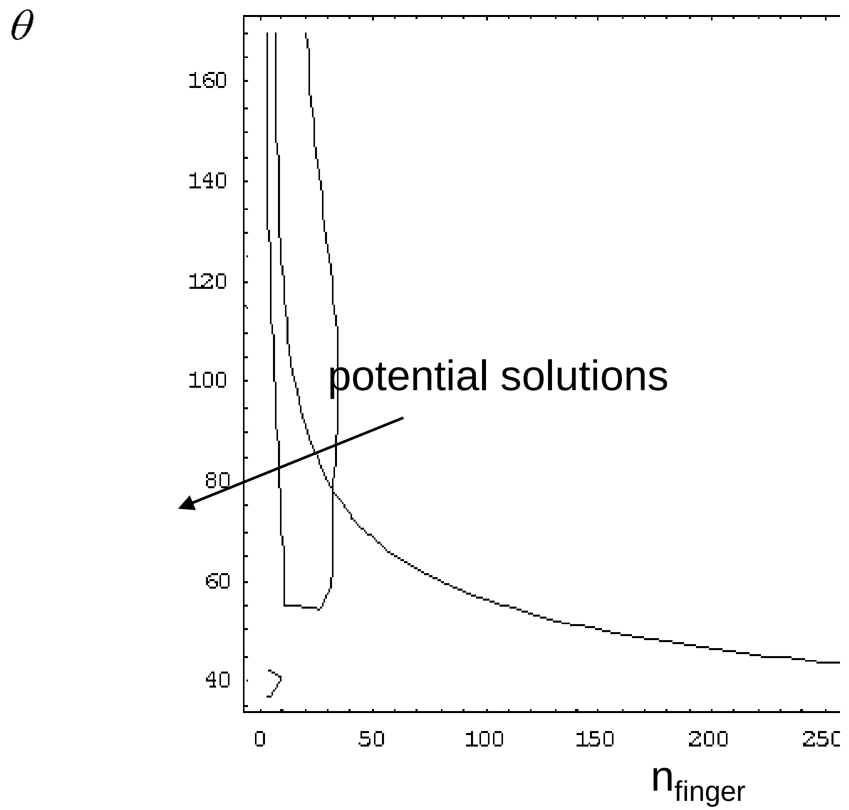
- Fingering is initial value problem
- Strongly nonlinear dependence of cross section of fingers
- Froude number in finger must exceed unity
- Spacing between fingers must exceed curvature radius resulting from zero mean curvature
- Fingering only occurs if circular hydraulic jump is not established at a smaller radius



Minimum finger spacing curves (d=2), ξ=.4

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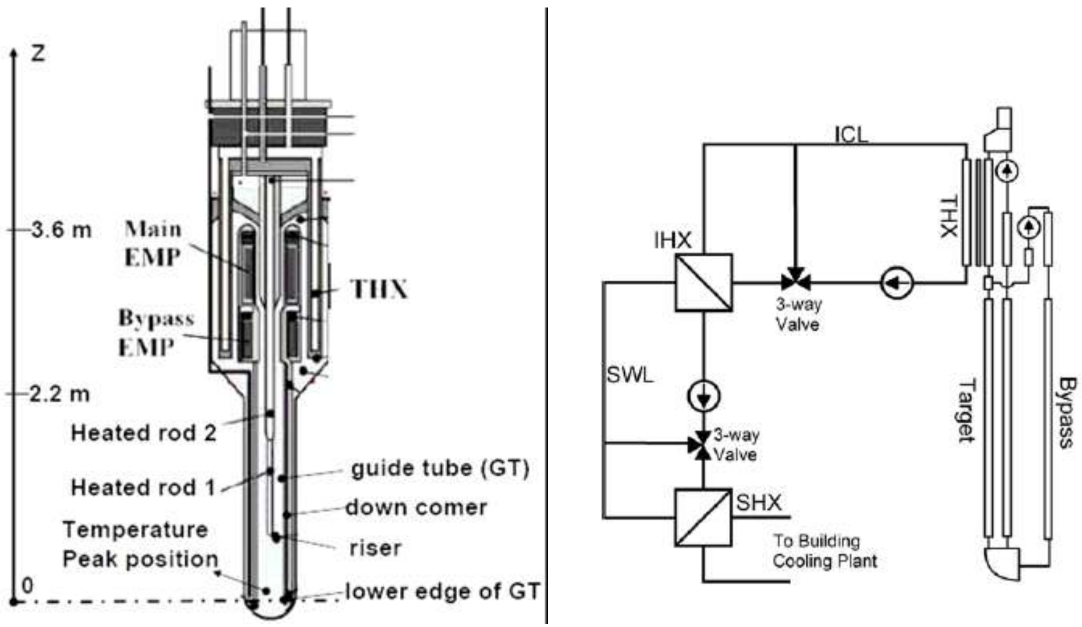
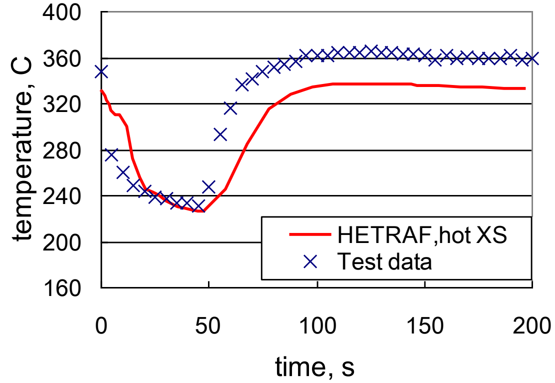
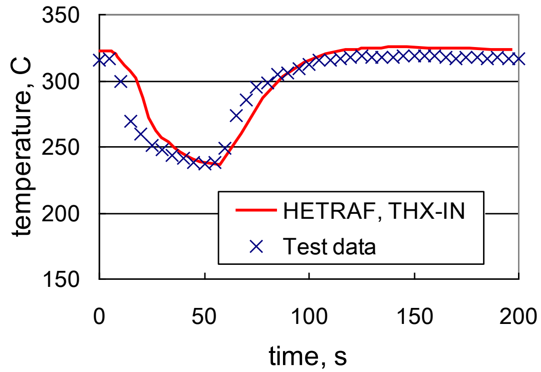
Application for the HETRAF Code for 1 D thermohydraulics analysis

Example of a beam trip of the MEGAPIE





(a) LBE temperature at THX inlet



(b) LBE peak temperature

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Summary

- In KALLA numerous experiments are performed which focus on component testing, HLM heat transfer, free surface flow, and HLM-instrumentation.
- Flow modeling group supports experiments by pre- and posttest calculations, improving the experiments design and interpretation of experimental data.
- CFD replaces experiments wherever possible.
- Accompanying fundamental studies allow improving confidence in CFD.

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