Numerical and Experimental Investigation of Turbulent Forced Convection Liquid Metal Heat Transfer along a Heated Rod in Annular Cavity

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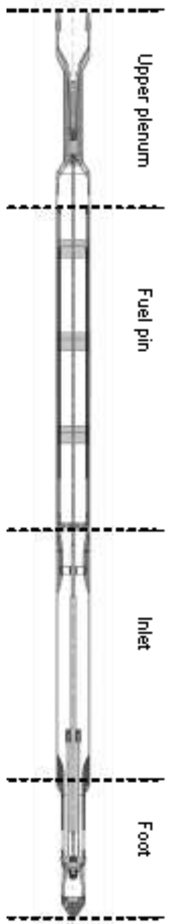
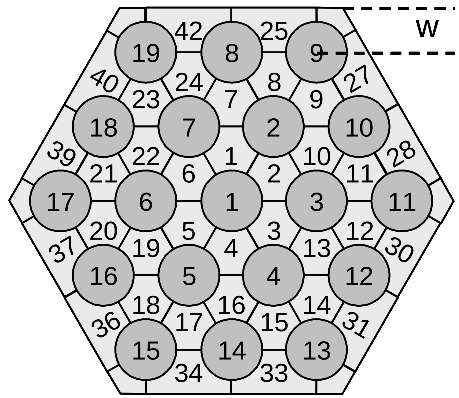
Rode bundle experiment for liquid metal cooled reactors

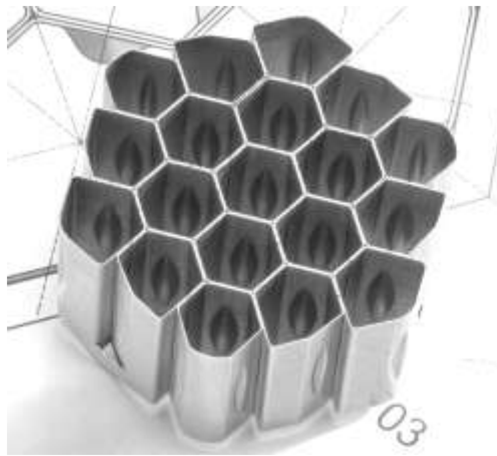
XADS_ASSEMBLY



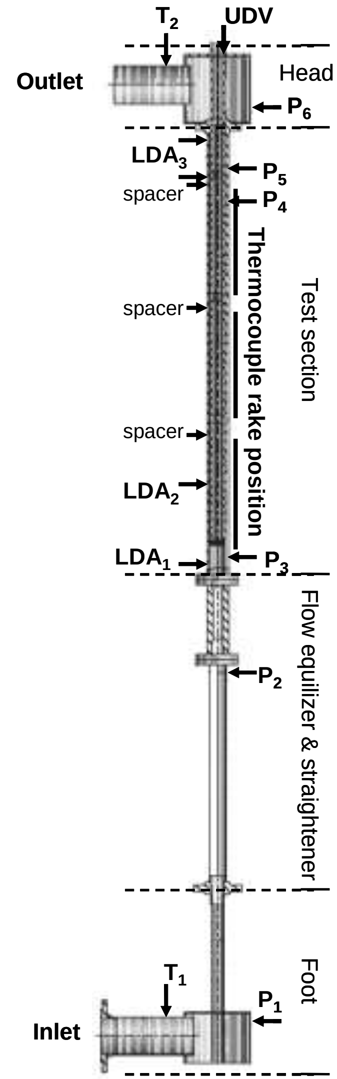
91 Pins/1.2Mw/6Rows

F 8.5mm/100W/cm2/870mm



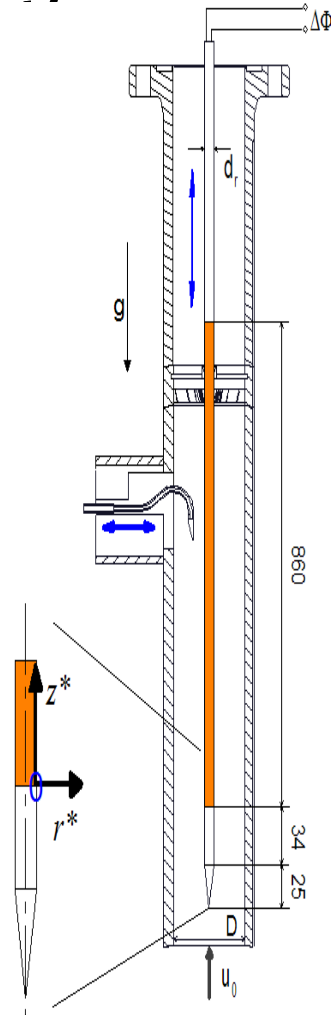


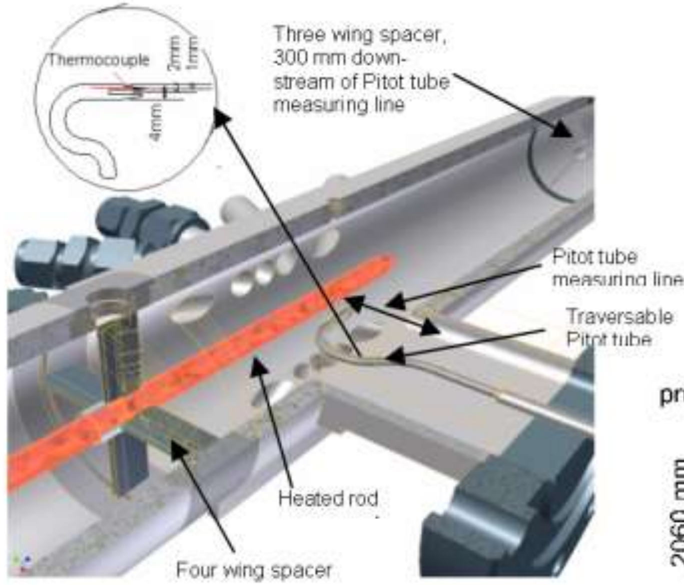
Cross section and spacers of tested heated rod bundle experiment at KALLA

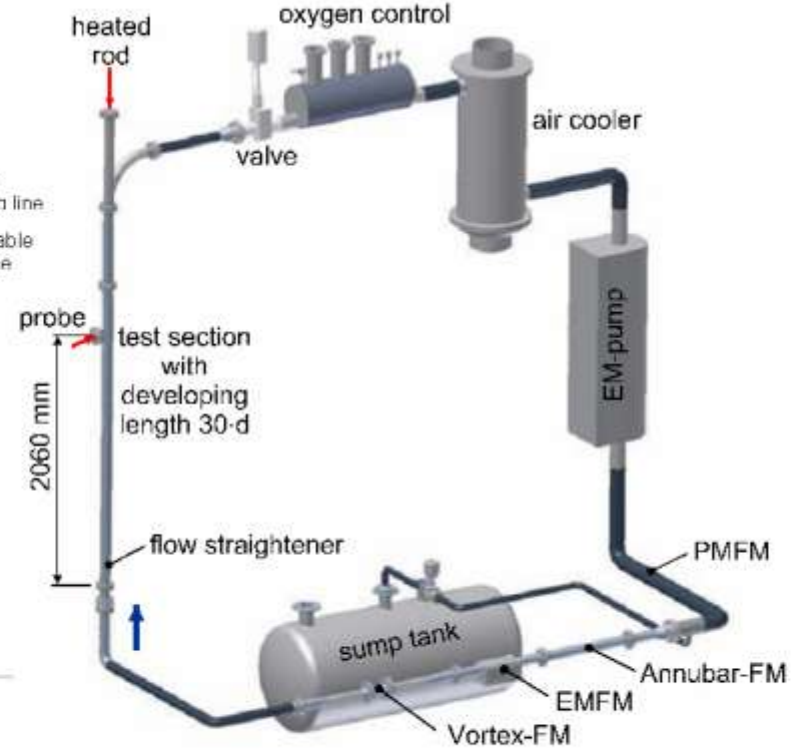


Heated rods bundle experiment set up

Single rode experiment



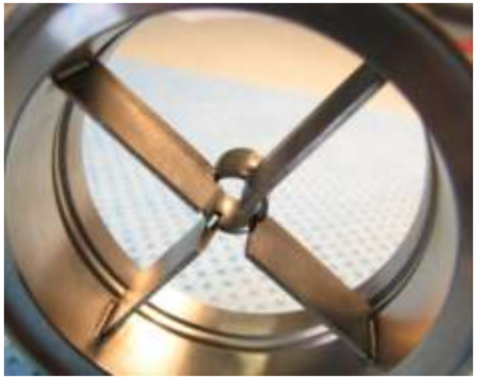


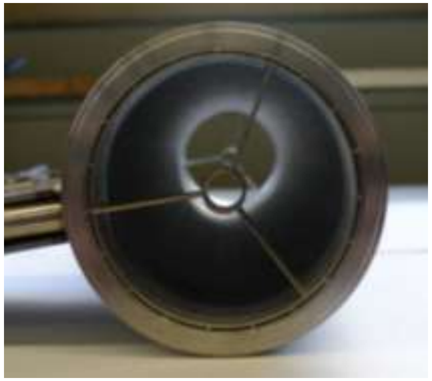


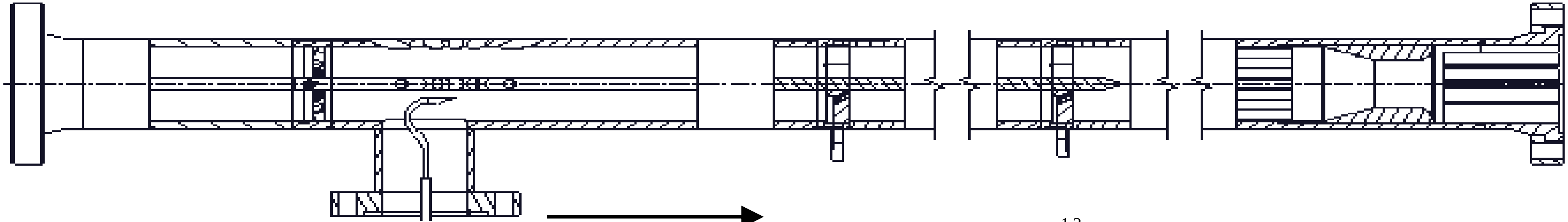
flow rate is recorded simultaneously using 4 physically different flow meters, an electro-magnetic frequency flow meter, a vortex flow meter, a pressure difference based system and a permanent magnet. Additionally, using a heat balance calculation the accuracy of the flow rate reading is ±0.3%.

2D and 3D CFD results are compared to experimental results for 8 m^3/h and 9kW

Used spacers and flow straightener







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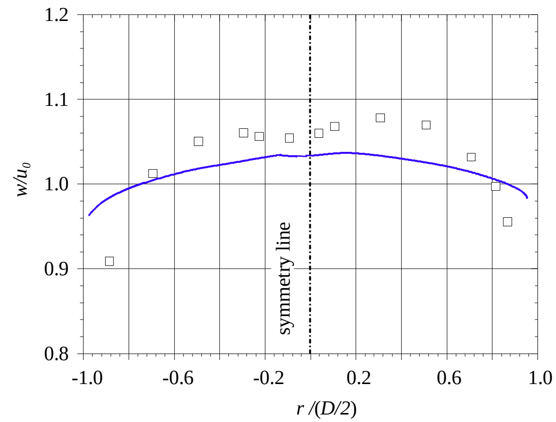
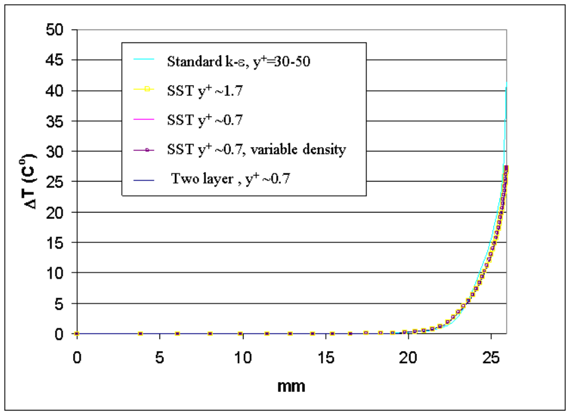
Without heater, measured and calculated streamwise velocity along the Pitot tube measurement plane (heated pin tip is downstream of measurement layer I) for a Re=3.1.10^5 based on the gap width pin-outer tube).



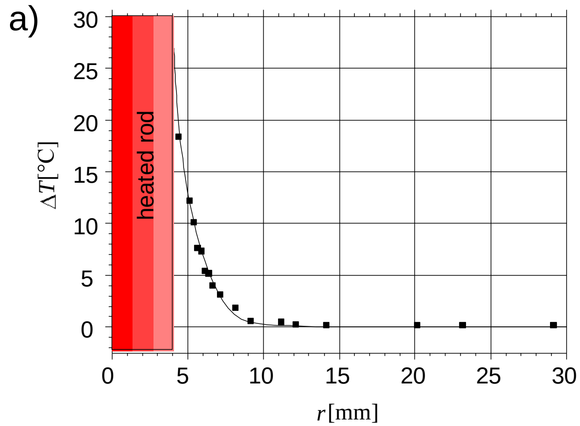
<u>Inflow is not 100% Uniform, or high turbulance effect,or …?.</u>

Earlier study considering details of heater

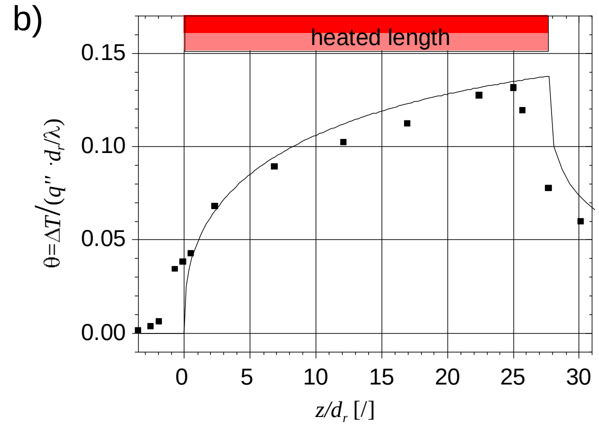
Short pin (l=228mm, q´´=3.4 105 W/m2, Re=2.7 10^5)



Radial temperature profiles at z/d=22.6 for demonstrating consistent results with the SST and the two-layer turbulence model for various grids with y+~1.



Meas. and calculated mean radial temperature profile at *z*/*dr*=22.6.

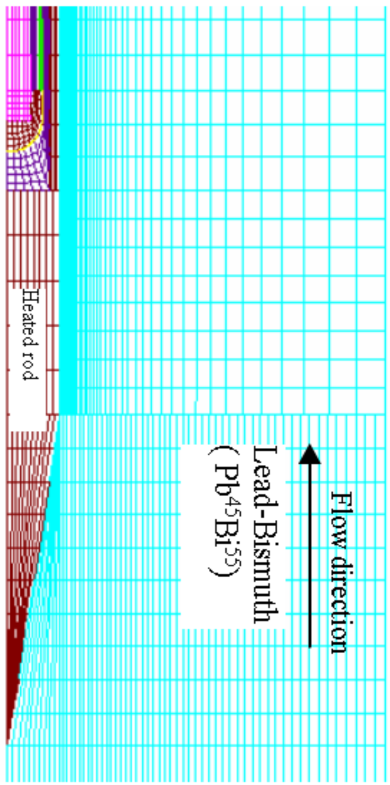


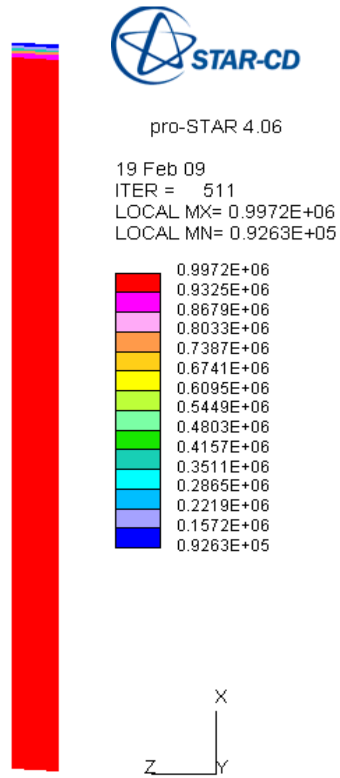
Meas. and calc. dim.-less axial fluid-wall interface temperature. Both for *Pr*=0.022 and Re=2.67.10^5.

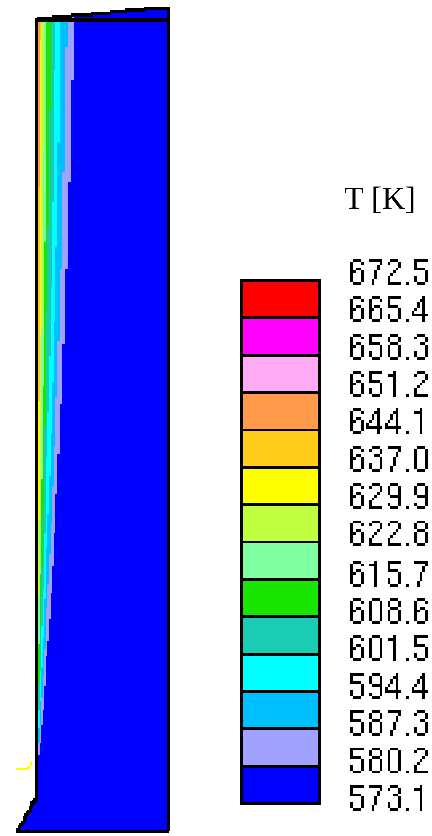
➡ SST model has good agreement with experiment.

Earlier study considering details of heater

Heated length, 800 mm, 0.8m/s , q''=100W/cm^2







Axis-symmetry, developing flow length of 1.223 m

➡ Near constant heat flux

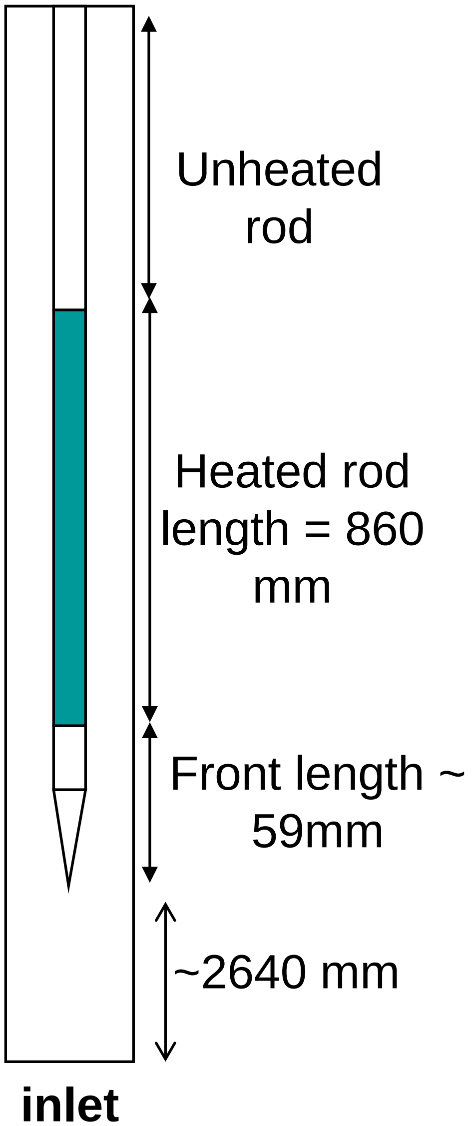
Constant heat flux or constant heat generation can be assumed.

2D CFD Study

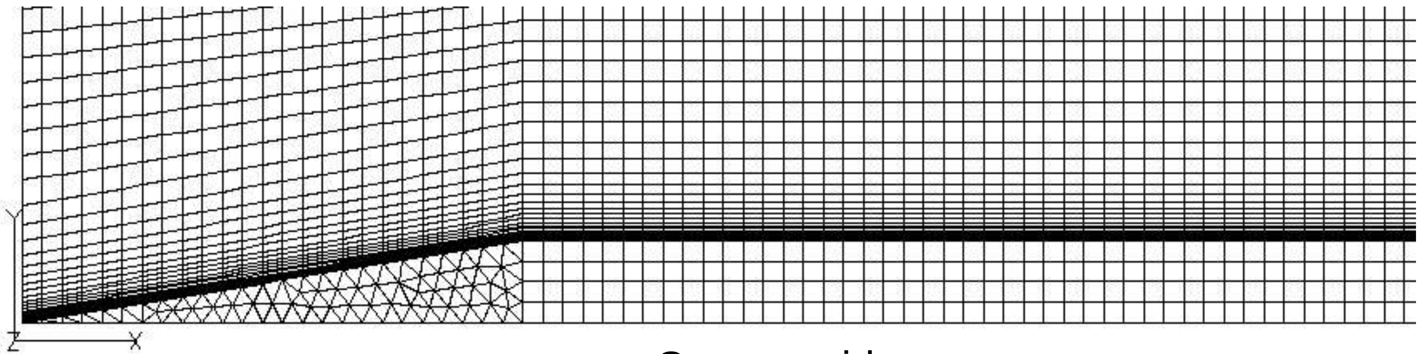
Computation with CFX using SST k-ω model (one of the suitable models based on short-pin computations), uniform heat generation

- Check the grid independence

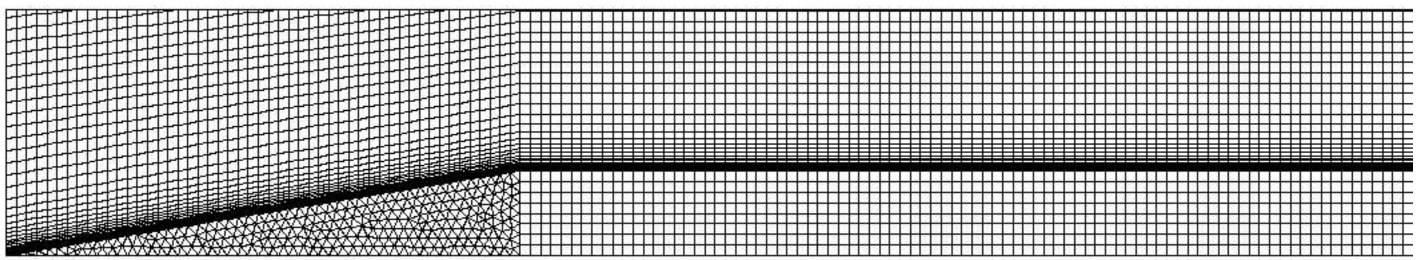
2D axisymmetric model (4°section model)
Working fluid: Lead Bismuth eutectic (LBE)
No-slip conditions on walls
Inlet:
specified uniform velocity of 0.773 m/s corresponds to the mass flow rate of 8 m^3/hr
temperature 300°C = 573.15 K
The heated rod is simulated by a uniform volumetric heat generation of 1.982 E+08 W/m^3 that corresponds to the power of 9kW.
The thick insulation of the duct allows adiabatic walls as first assumption



Geometry & Model



Coarse grid



Fine grid

Number of computational volumes: about 69 000 for the coarse grid and 230 000 for the fine grid

Y+ ~ 3 for the coarse grid and ~1.5 for the fine grid

Geometry & Model

- Temperature dependent properties of LBE (taken from OECD Handbook)

- Constant properties of Stainless Steel 1.4571 DIN for the rod

- Employed computational code CFX:
  - SST k-ω model with automatic wall treatment
  - With and without buoyancy term in the production of turbulent kinetic energy and frequency (Remark: Buoyancy is indicated in the figure legend).
  - In forced convection buoyancy is expected not to play a major role

Non-dimensional Representation

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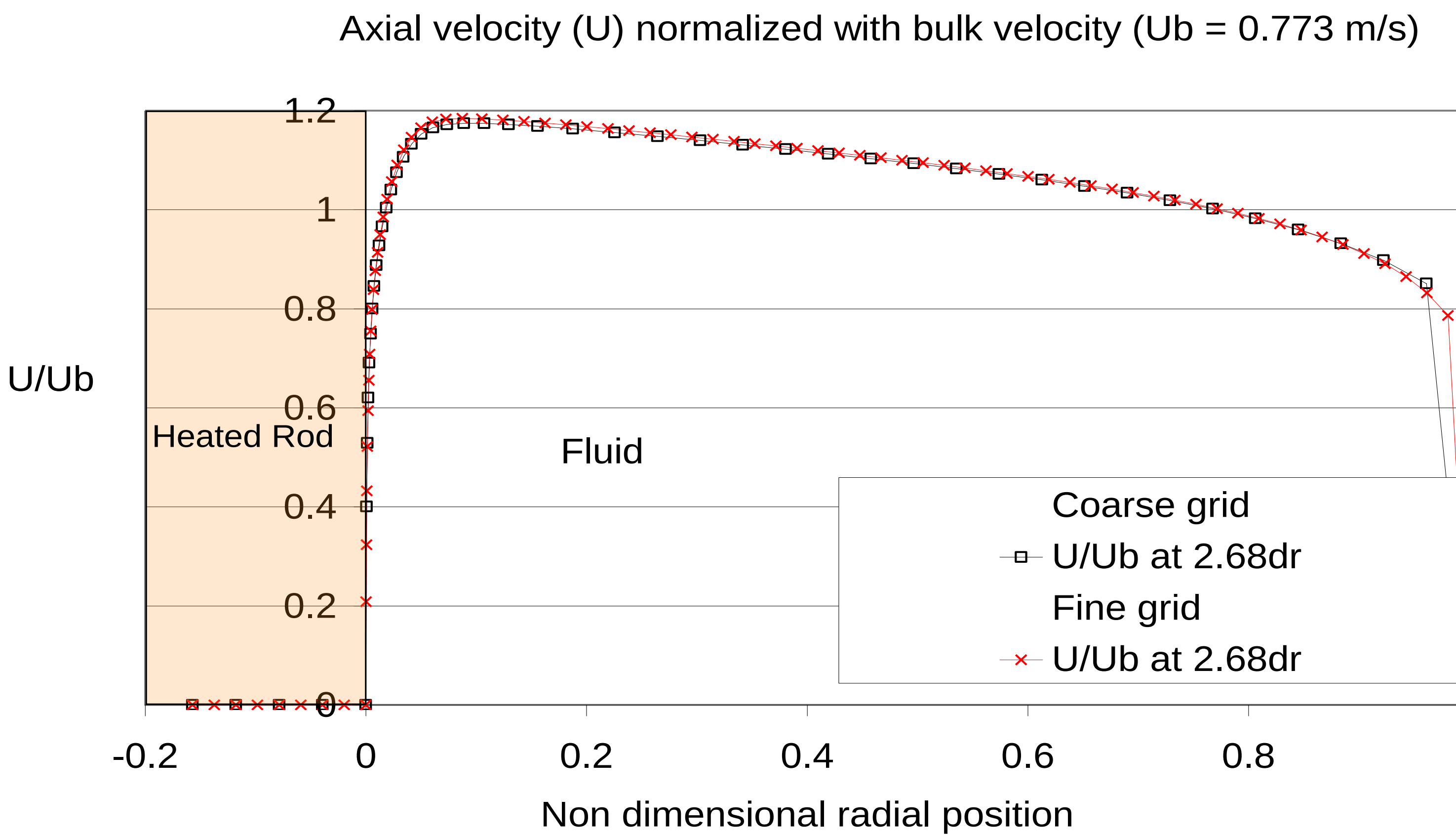
- Dimensionless axial length (ξ)
  - $\xi = (x) / d_{rod}$
    - in which d_{rod} is the heated rod diameter (this is indicated by dr in the figures)

- Dimensionless radial position ($\hat{y}$)
  - $\hat{y} = \{y-(d_{rod}/2)\}/\{(D/2)-(d_{rod}/2)\}$
    - D is the diameter of test section

- Dimensionless temperature ($T_{non\text{-}dim}$)
  - $T_{non\text{-}dim} = 1/Nu = (T - T_{in}) \cdot DT$
  - $DT = q_w \, d_{rod} / \lambda$

Results long pin

Normalized axial velocities with different grids

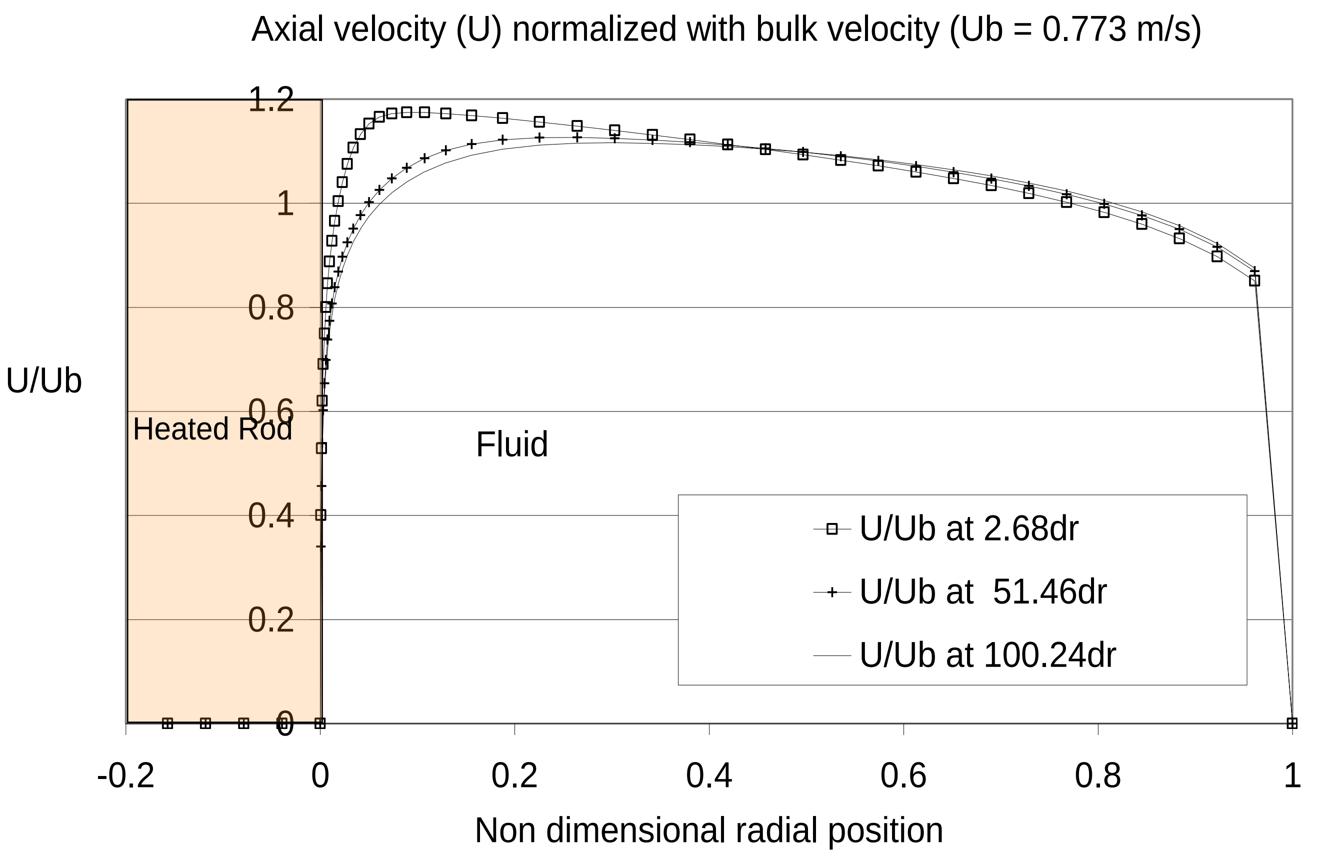


Differences near the insulated cold wall, which is indicated by 1 in the picture, are attributed to the considered large grid width e.g. in coarse grid the *Y*+~100.

► Computed axial velocity is considered grid independent near the heated rod.

Results Long Pin

Non-dimensional velocity with CFX for the coarse grid

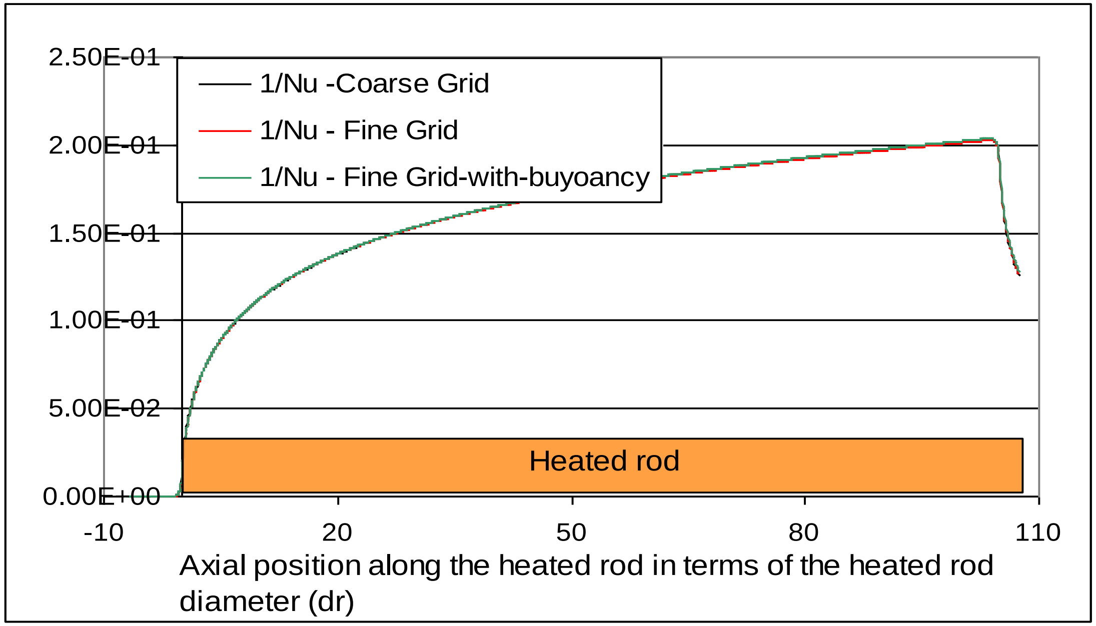


The viscous boundary layer near the heated rod (indicated by '0' non-dimensional position) is resolved.

Analyzed computed results reveal that coarse grid contains 4 and fine grid contains 7 cells in the viscous boundary layer defined by *y+~10 (which is ~0.0007 mm).*

2D CFD Results

Non-dimensional axial temperature computed with different grids



Grid	Highest 1/Nu
Coarse	0.203
Fine	0.203
Fine (with Buoyancy)	0.204

The computed results are practically grid independent.

Buoyancy has negligible influence on the 1/Nu or non-dimensional temperature.

The 1/Nu number increases rapidly as the fluid comes in contact with the heated rod (indicated by ‘0’ in the above picture).

The maximum of 1/Nu ~0.2 is achieved near the end of the heated section (given by non-dimensional axial length of 103.65).

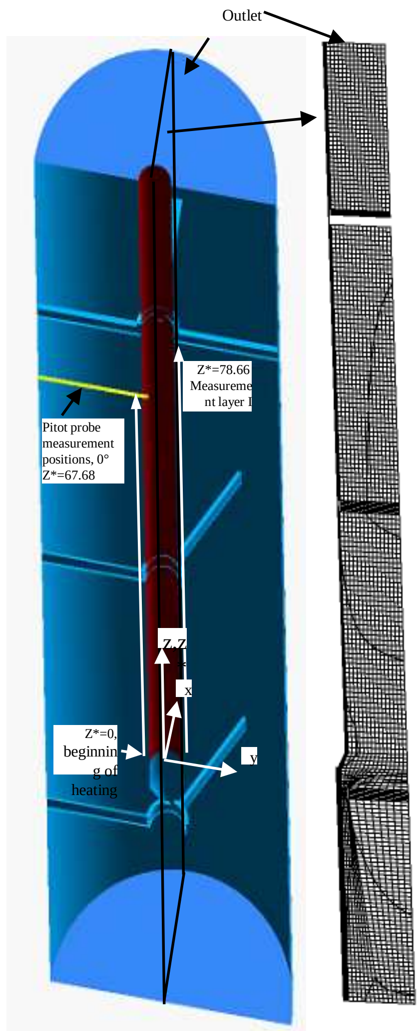
3D CFD Study

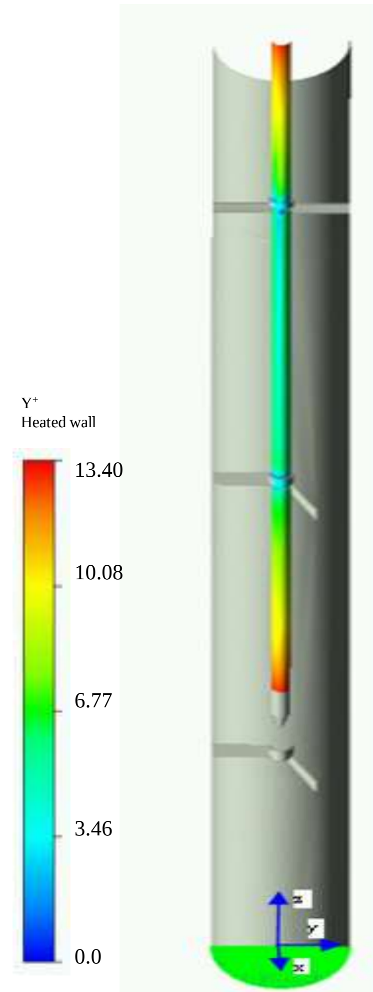
•SST model

•constant fluid properties

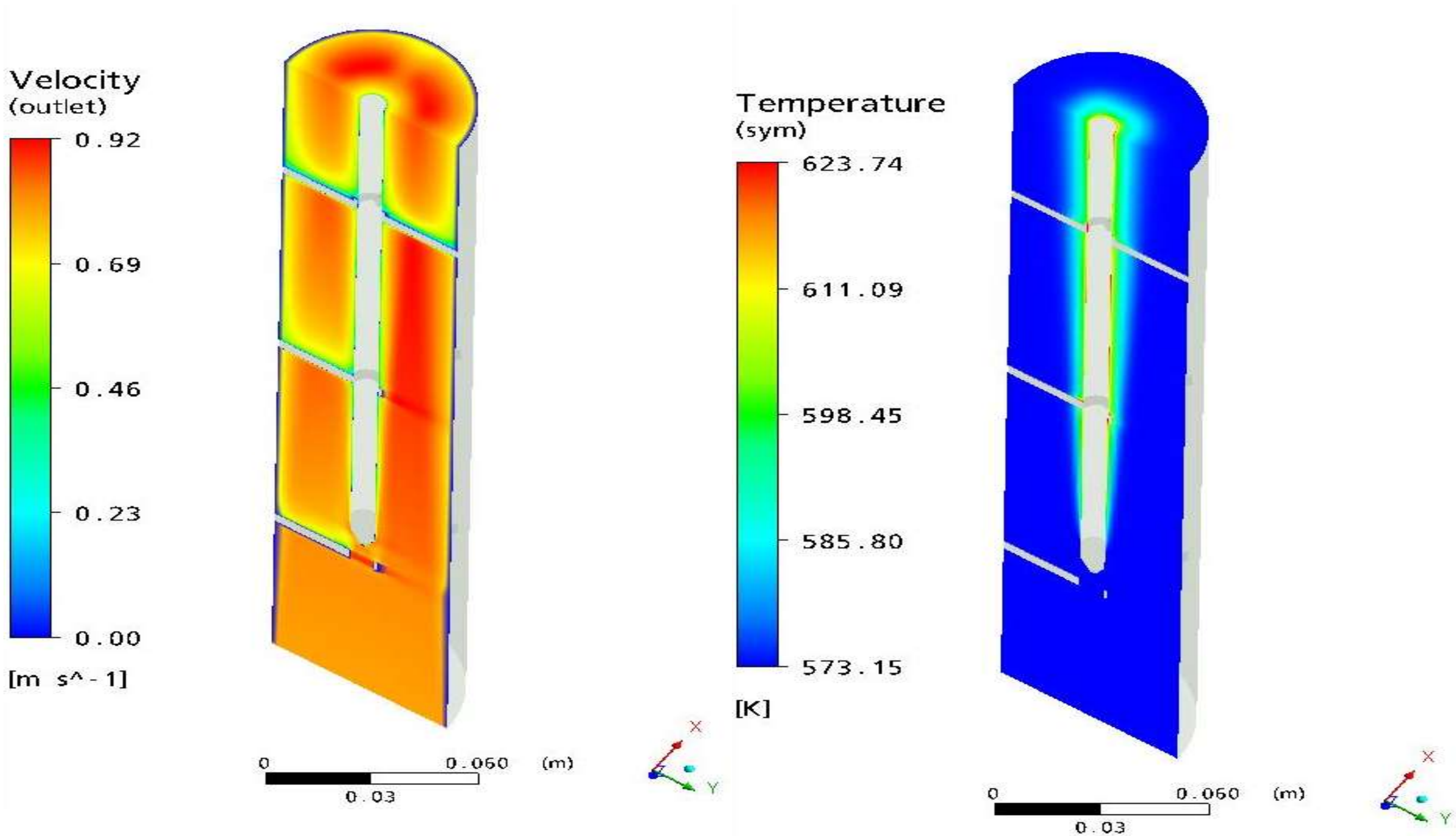
•studied case corresponds to rod tip position z=704mm from the measurement layer 1. Considering the unheated pin length which is 59mm, the dimensionless *z** for this case is equal to *z**=(704-59)/8.2=78.66

$$r^* = \frac{r - d_r/2}{D/2 - d_r/2}, \quad u^* = \frac{u}{U_0}, \quad z^* = \frac{z}{d_r}$$

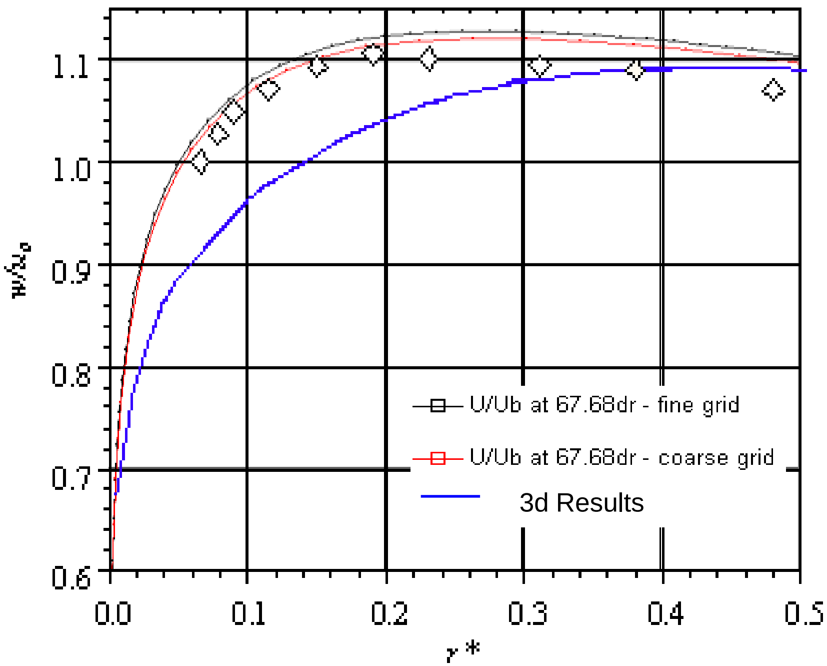


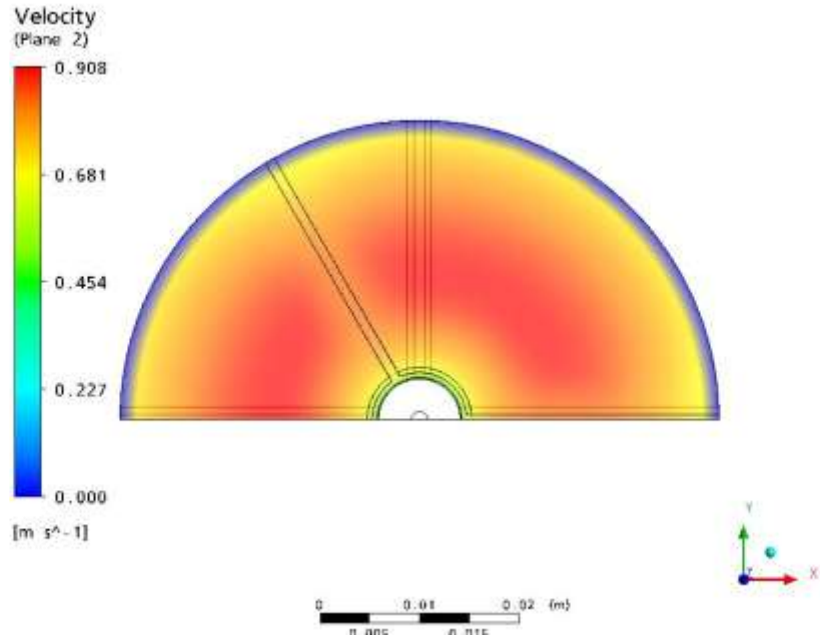


velocity and temperature contours at outlet and at symmetry plane



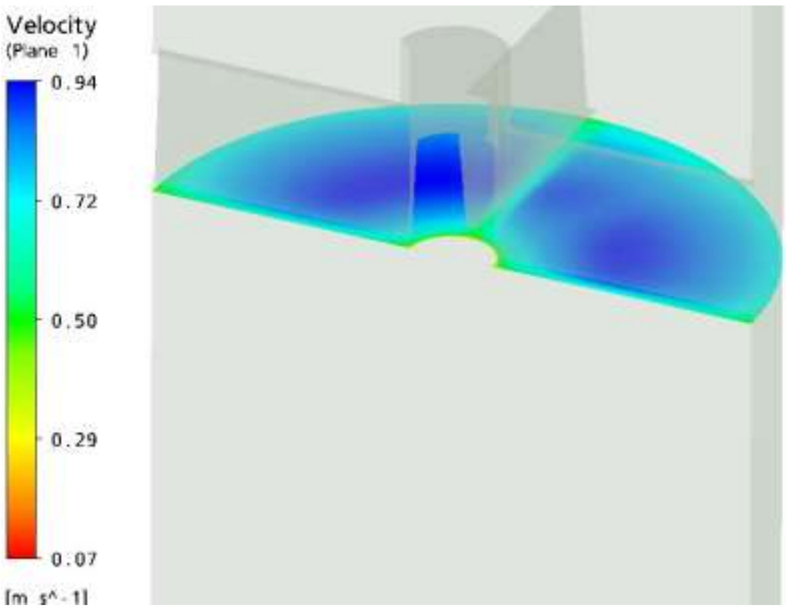
Velocity comarison at z*=67.68 and θ=0°

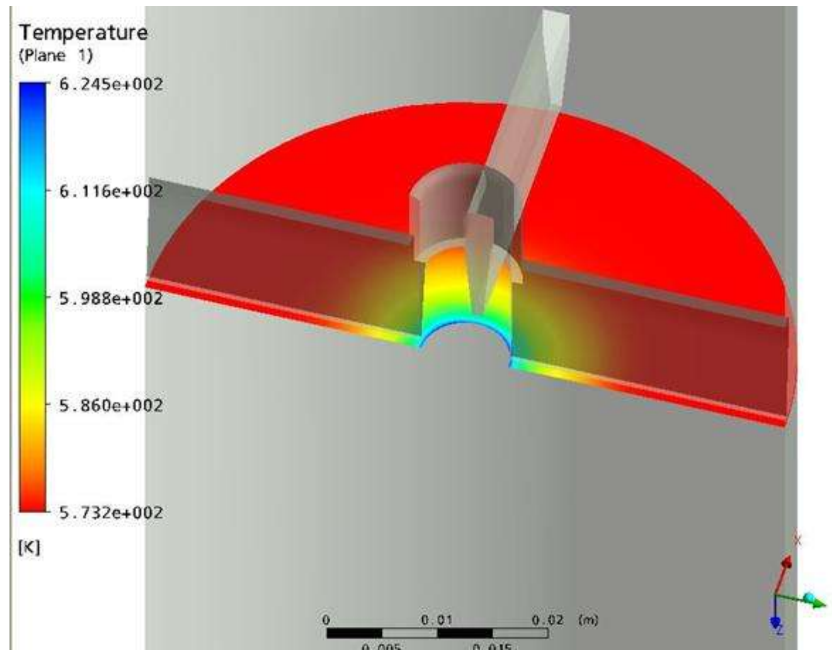




2D results agree with experimental, 3d predict lower velocity near wall

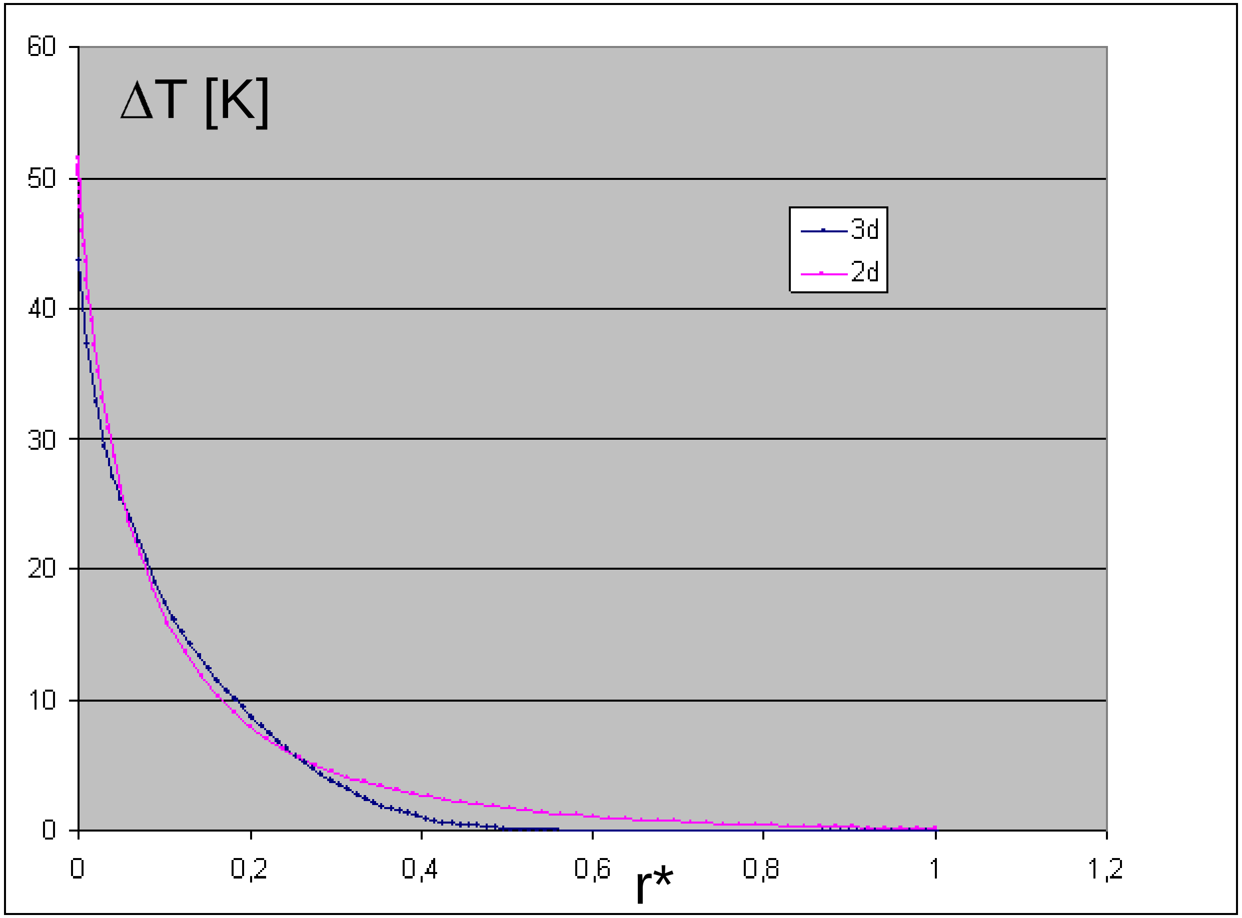
Temperature and velocity contours at measuring layer under spacer



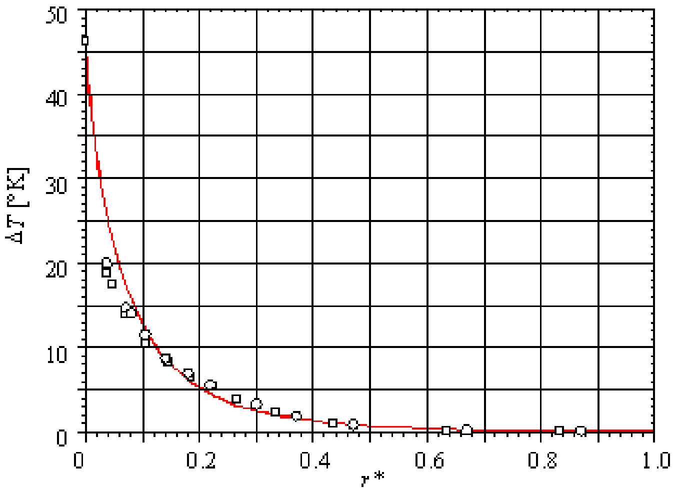


3d results shows that spacer influence temperature and velocity fields even far downstream of spacer

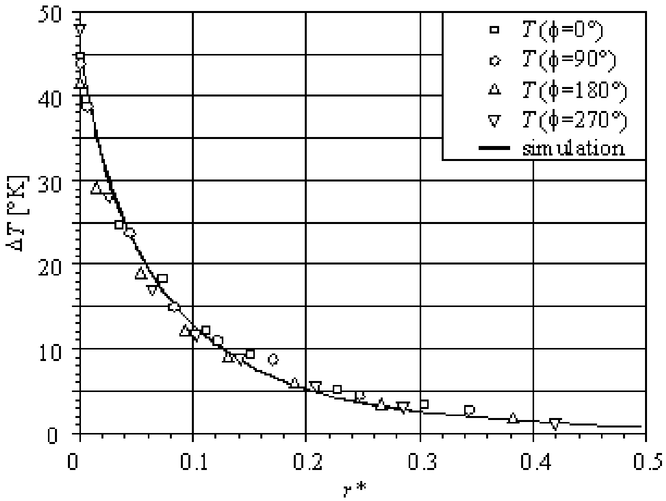
Temperature comparisons, numerical results



Temperature comparison at z*=51and θ=0°



Pitot tube TC's



Spacer TC's

Summery

- Turbulent forced convection liquid metal heat transfer along a heated rod in annular cavity is numerically and experimentally investigated
- Relatively good agreement between numerical and experimental results is obtained
- The obtained asymmetry in the experimental results indicates that inflow to test region can be the main reason for observed asymmetry since uniform flow is assumed . Consequently, the flow straightener region should be considered in the simulated