The University of Manchester

Project FORTE

BEIS Digital Nuclear Reactor Design Thermal Hydraulics – Phase 1

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Advanced modelling methodology development

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Introduction & Overview

- Output of two work sub-packages under Phase 1 of the BEIS Digital Nuclear Reactor Design program
- Overall focus is on advanced CFD modelling methodologies
  - utilizing and exploring advanced CFD models
    - advanced wall-functions, non-linear, stress-transport models etc.
  - application to novel systems (passive cooling)
  - application to multi-phase flows and boiling

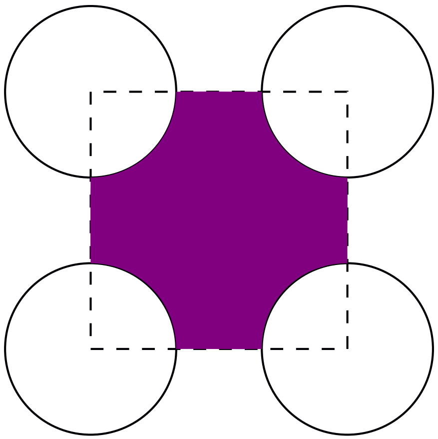
- Presentation Overview
  - **Single-phase**
    - Fuel passage subchannels
    - Natural Circulation Loops
  - **Multi-phase**
    - Rod-bundle boil-off

Fuel passage Subchannels

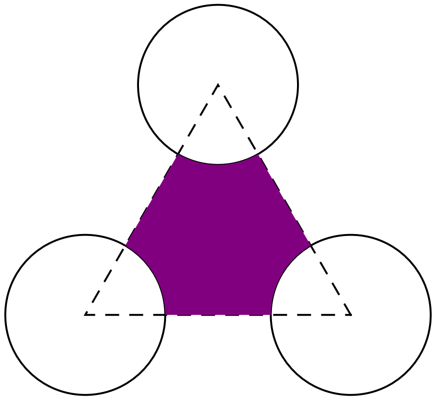
2D RANS

Fuel Subchannels

- At their most basic, fuel assemblies are simply collections of cylindrical fuel rods.
- Rods are typically arranged in square, triangular or circular arrays.
- Subchannel thermal-hydraulic behaviour is critical to reactor safety and performance.
  - Rate at which thermal energy is removed determines peak reactor temperature.
  - Can impact fuel rod integrity.
- **Objective is to assess the potential of state-of-the-art RANS turbulence models in reproducing these flows.**
- To do that we need data..



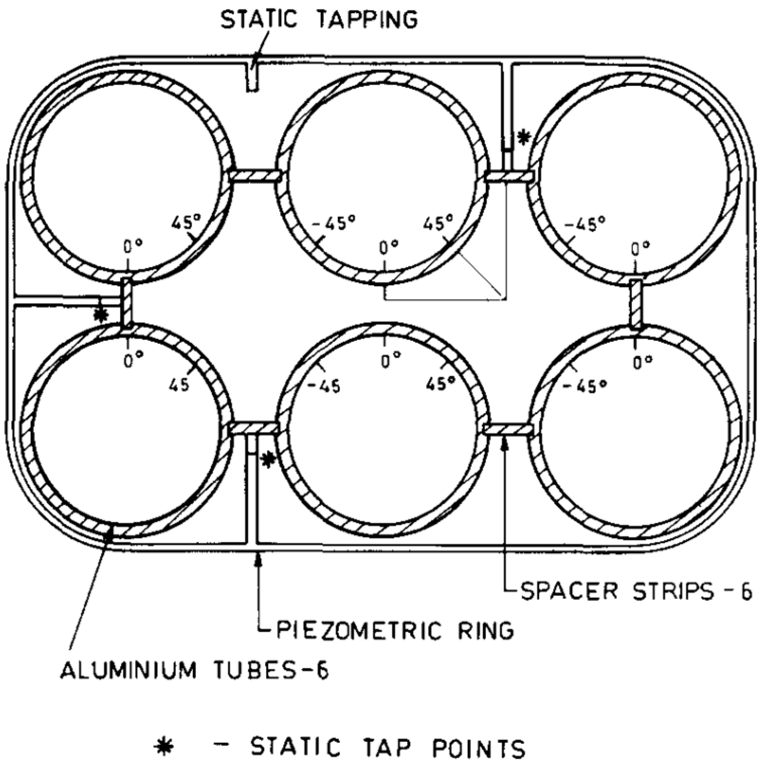
Square array



Triangular array

Experimental data

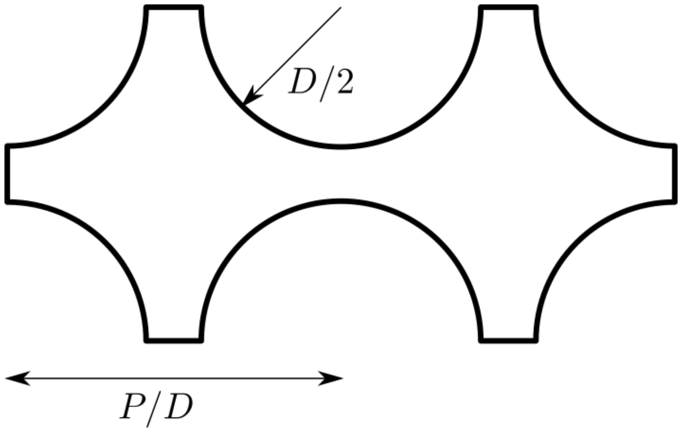
- Experimental study by Hooper (1980, 1984)
- Flow of air through a 2x3 square pitched rod bundle array.
- $Re = 48000$, $P/D = 1.194$
- Fully developed: $95D_h$
- Data includes:
  - Wall shear stress
  - Axial velocity profiles
  - Reynolds stress profiles



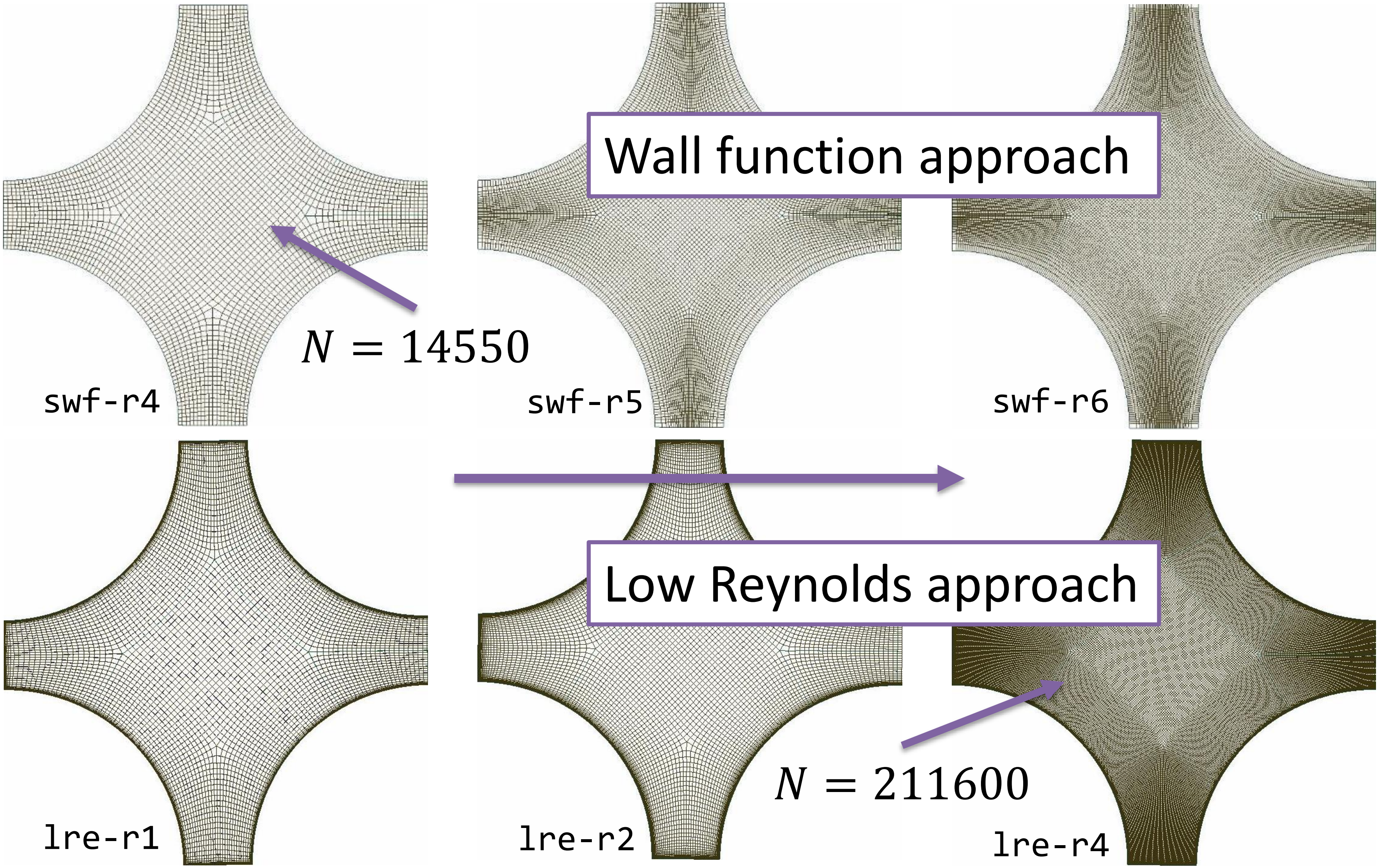
Cross-section of Hooper's geometry

Numerical methodology

- Fully-developed – axial periodicity employed (1 cell thick)
- Full wall-bounded twin subchannel geometry of Hooper (1980)
- Two types of mesh considered:
  - $y^+ \approx 1$ for integration through the viscous sublayer with low-Re models
  - $y^+ \approx 30$ for use with wall-functions – both standard, and more advanced, formulations considered.
- Selection of turbulence models covering the three main classes:
  - Linear eddy-viscosity models (LEVM)
  - Non-linear eddy-viscosity models (NLEVM)
  - Reynolds stress models (RSM)

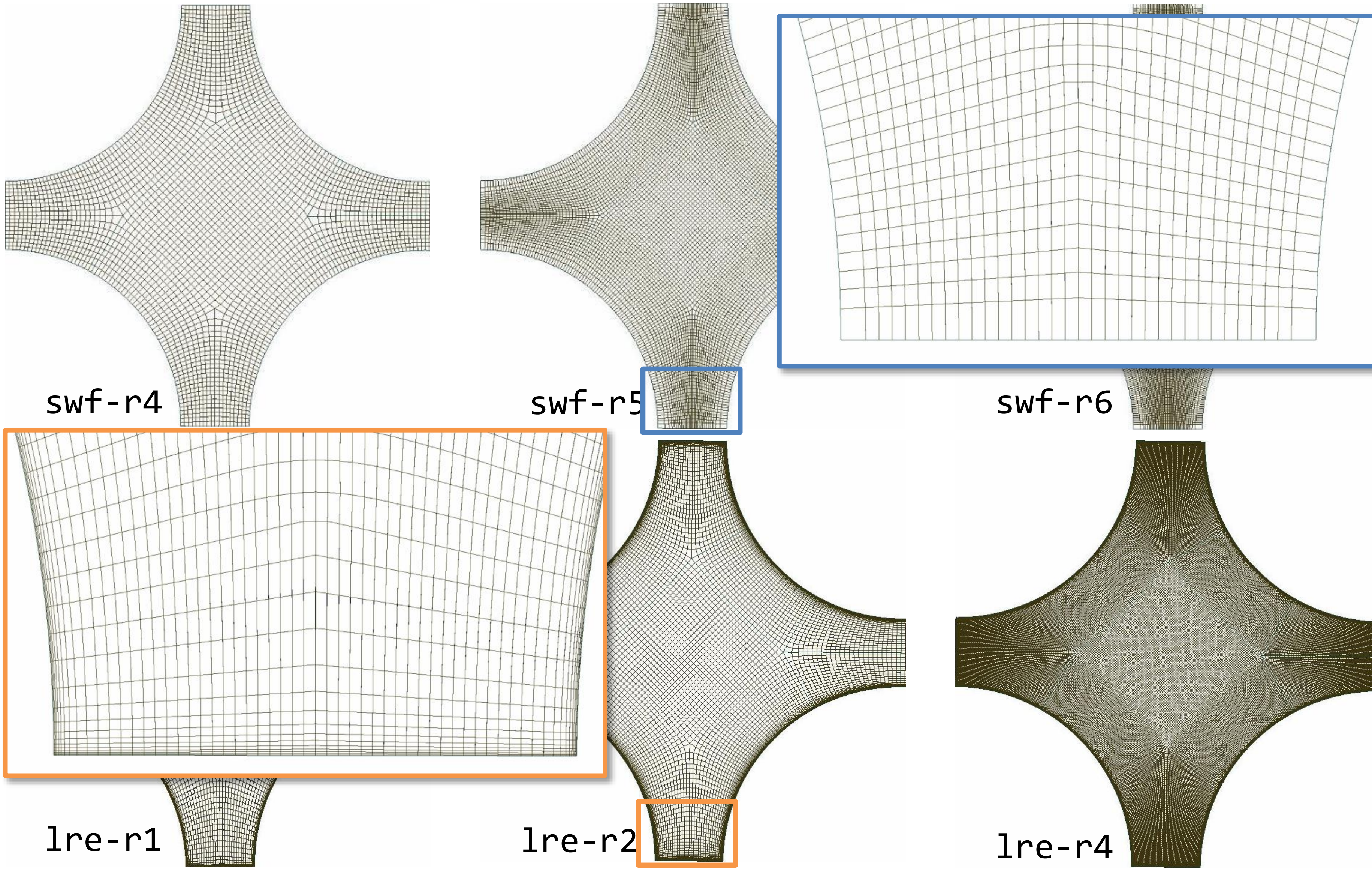


Mesh set-up



Wall function approach
$N = 14550$
swf-r4
swf-r5
swf-r6
Low Reynolds approach
$N = 211600$
lre-r1
lre-r2
lre-r4

Mesh set-up



Wall function formulations

- **Standard wall-function (SWF)**
  - '*law-of-the-wall*' assumes local equilibrium.
  - Provides an expression for the velocity at the first near-wall node – wall shear-stress and other quantities follow.
- **Analytical wall-function (AWF)**
  - Instead of using a log-law, uses a simplified version of the near-wall momentum equation:

$$\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial U}{\partial y}\right] = -\frac{\partial P}{\partial x} + C_u + F_u$$

Convective terms (C_u)

Body forces (F_u)

  - With a prescribed near-wall variation of turbulent viscosity, and suitable approximations of the other terms, the momentum equation can be integrated twice to obtain an expression for U.
  - Wall shear-stress and other quantities follow, similar approach for the energy equation.
  - Allows convection, pressure gradient and body force effects to be captured

Computations performed

- Wall function approaches

Mesh	Nodes	HR	GL	CL
swf-r4	14500			
swf-r5	36880			
swf-r6	74100			

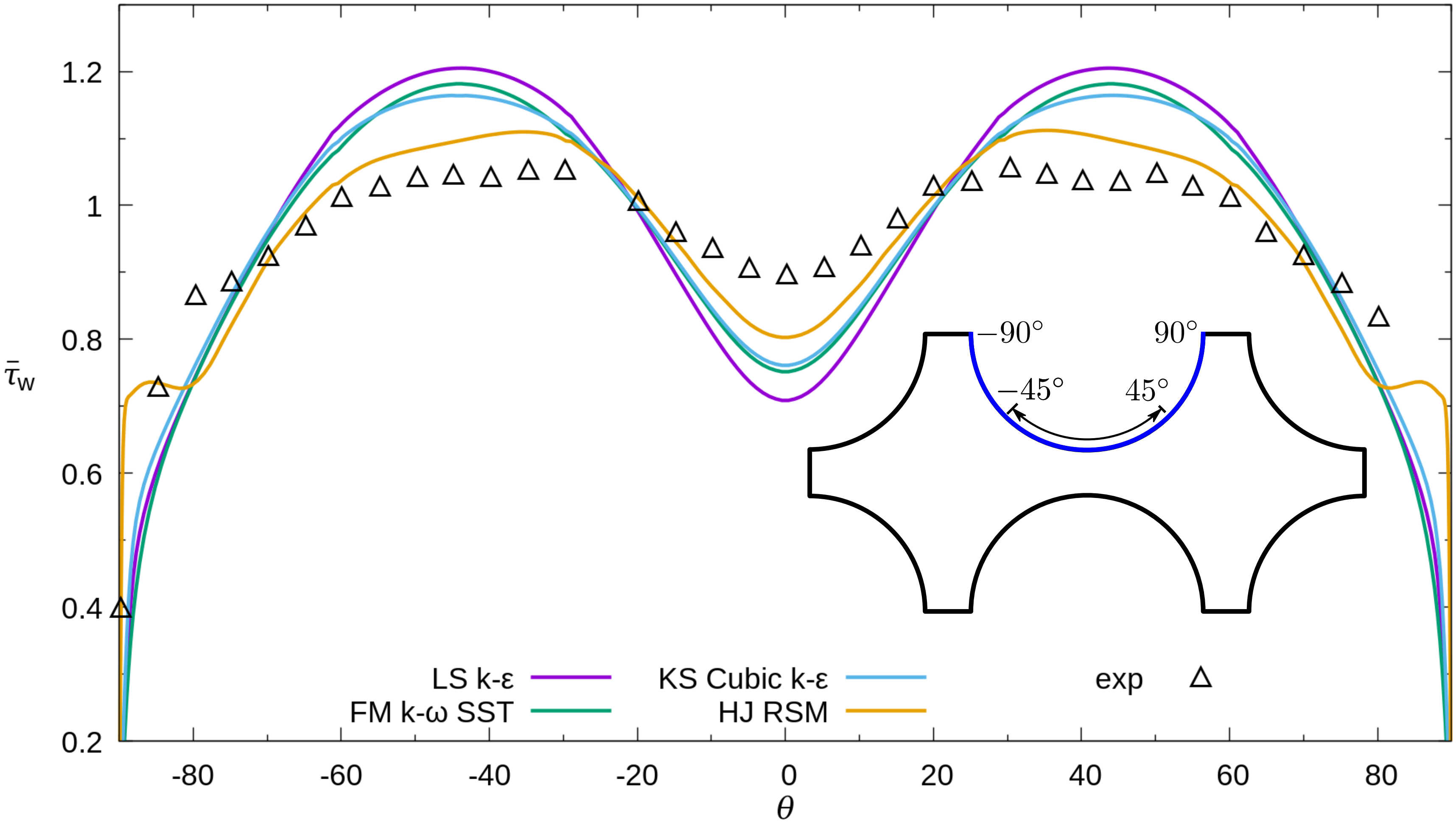
- Low-Re approaches

Mesh	Nodes	LS	FM	KS	HJ
lre-r1	45700				
lre-r2	52800				
lre-r3	101200				
lre-r4	211600				

- Variety of models tested:

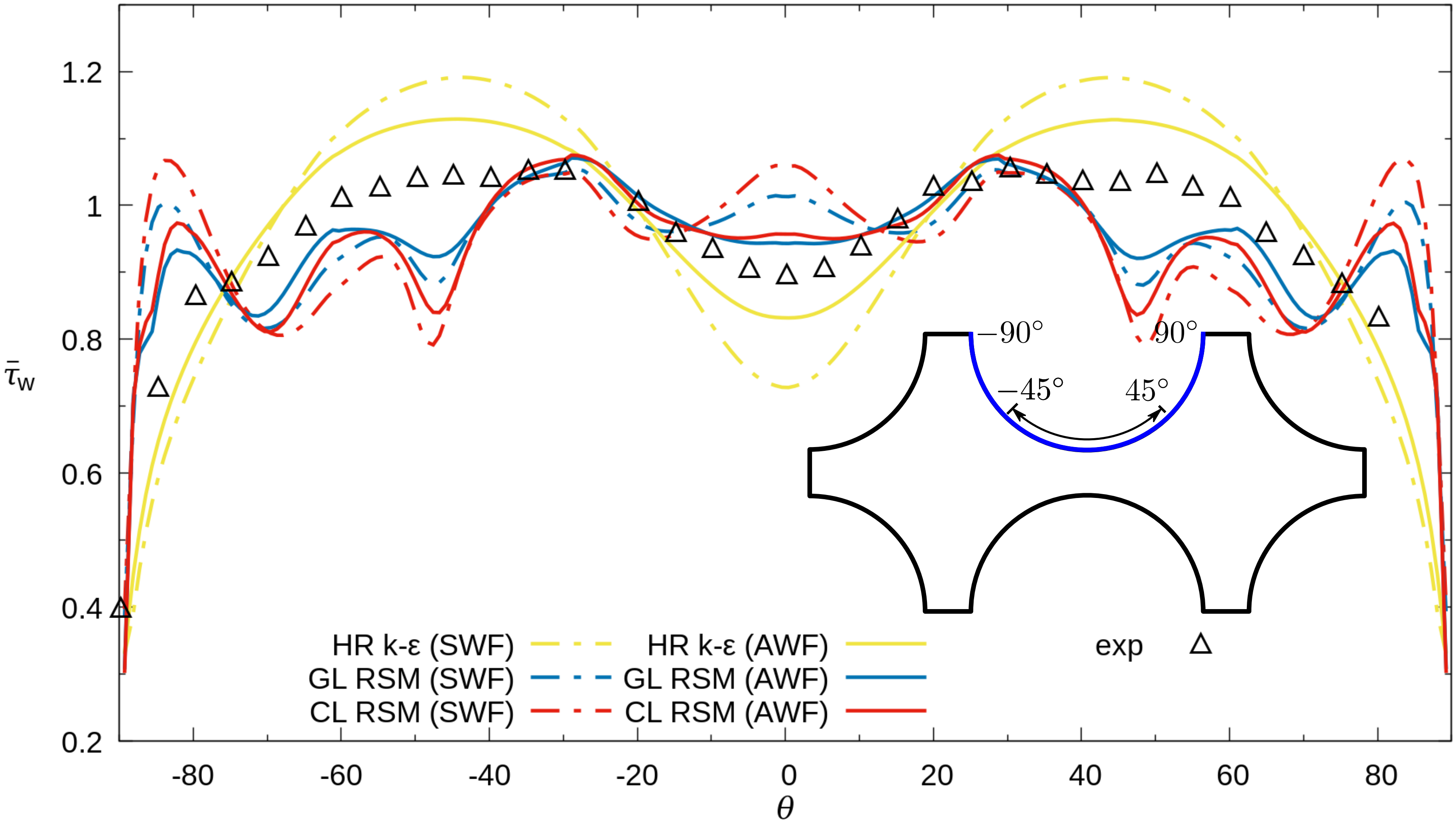
HR	LEVM	High-Re 'standard' $k–\varepsilon$	Launder-Spalding (1974)
GL	RSM	'Basic' high-Re closure with wall-reflection	Gibson-Launder (1978)
CL	RSM	As GL with modified wall-reflection	Craft-Launder (1992)
LS	LEVM	Low-Re 'standard' $k–\varepsilon$	Launder-Sharmer (1974)
FM	LEVM	$k–\omega$ SST	Menter (1994)
KS	NLEVM	Cubic $k–\varepsilon$	Craft et al. (1996)
HJ	RSM	Low-Re closure w/ wall-proximity effects	Hanjalić & Jarkilić (1996)

Results: Low-Re Wall shear stress



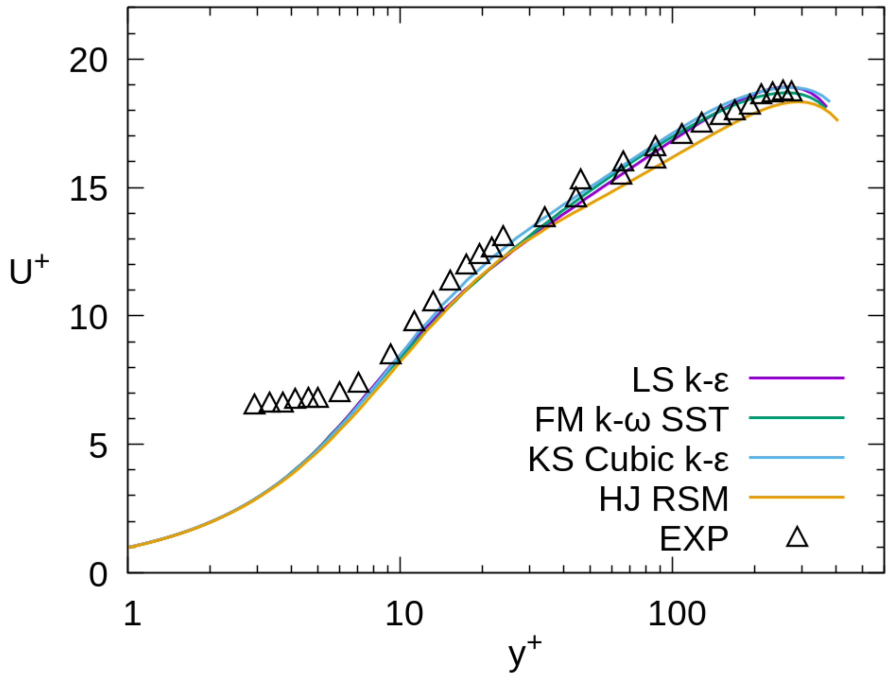
- All low-Re give qualitatively correct profile.
- Low-Re RSM provides closest quantitative agreement

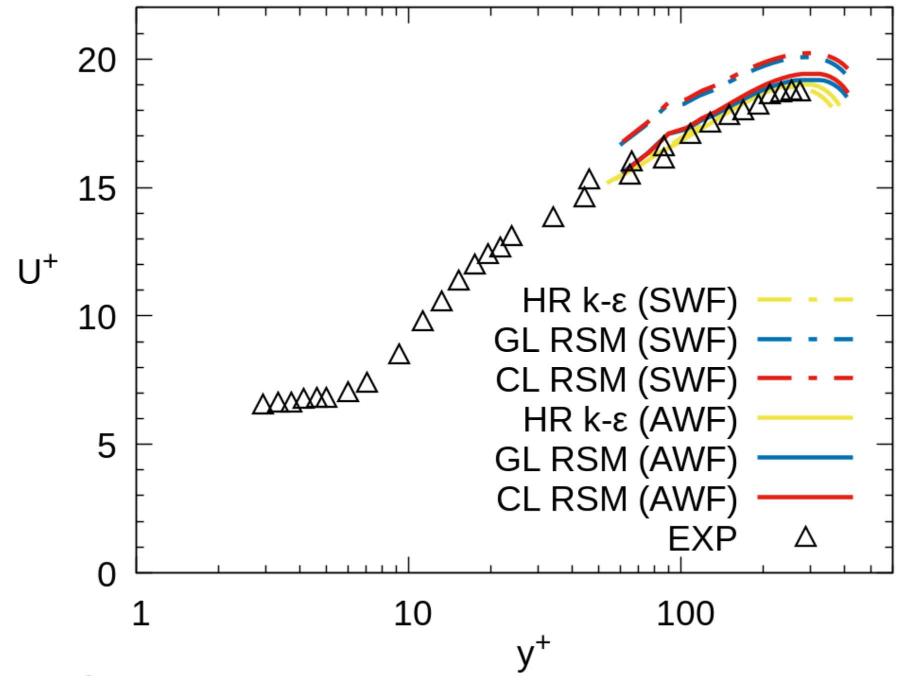
Results: High-Re Wall shear stress

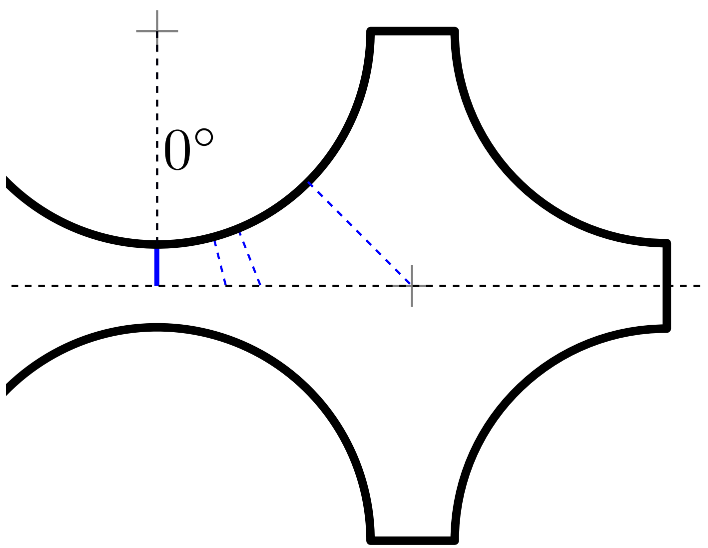


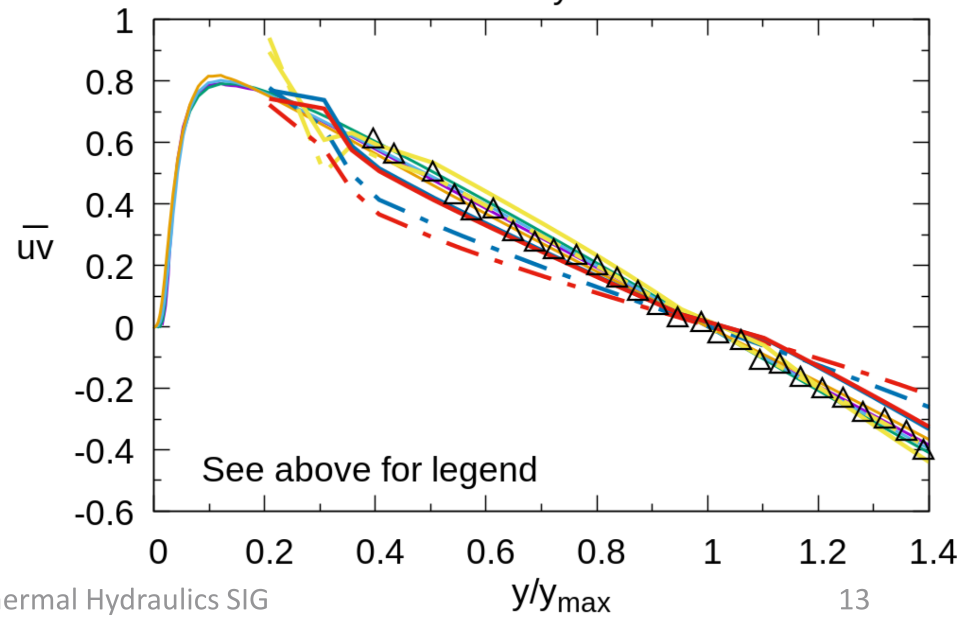
- Wall function RSM struggles: ‘dip’ at +/- 45° due to convective effects implied by the (correct) secondary motion the RSM captures.
- AWF formulations offers improvement.

Results: Profiles at 0°

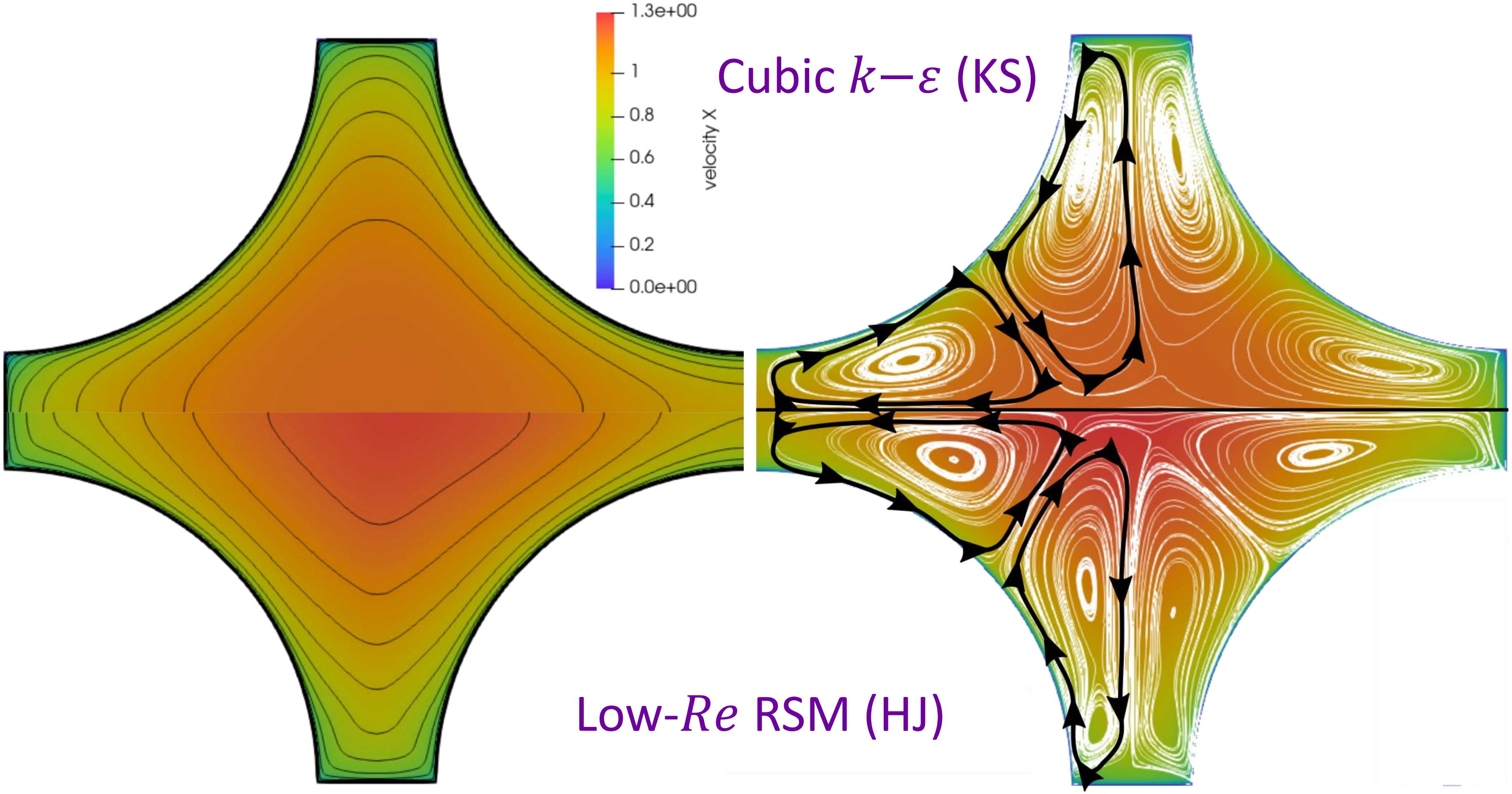








Secondary motion



- Secondary flow picked up by NLEVM and RSMs (only HJ shown).
- Much weaker, however: 0.31% (NLEVM) vs. 2.1% (RSM) of mean axial velocity.

Preliminary findings

- **Standard wall-function approach with an RSM fails to correctly predict the wall shear stress**
  - Incorrectly produces dips in wall-shear stress at +/- 45 (secondary flow separation points)
  - Analytical wall function, which captures near-wall convection and pressure-gradient effects, demonstrates improvements.
- **Low-Re RSM gives best agreement with experimental data.**
  - Superiority of the low-Re approach can be seen; should always be used if computational resources allow.
- **Subchannel type geometries generate anisotropy in the normal stresses, which creates secondary motion.**
  - Only a NLEVM or RSM will be capable of capturing this.
  - NLEVM produced qualitatively correct pattern, but flow was an order of magnitude weaker than that of the RSM.

Natural Circulation Loops

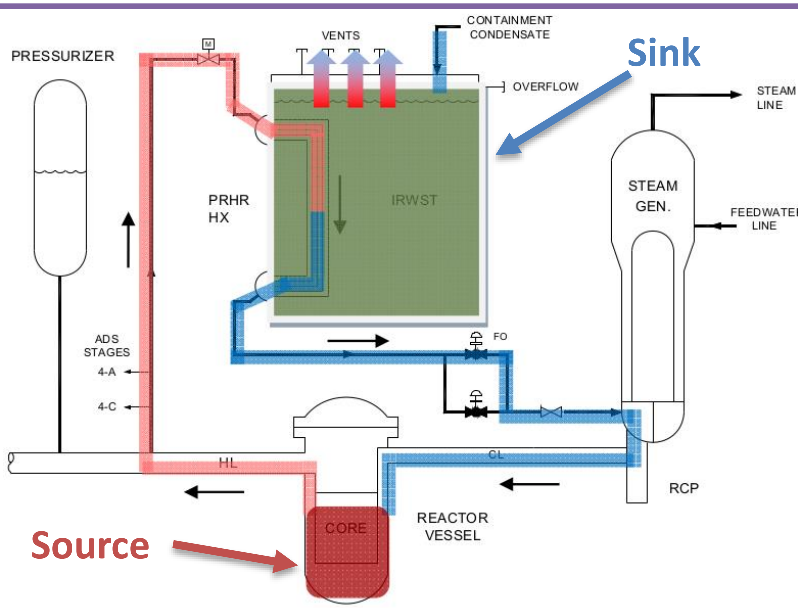
2D RANS

Natural Circulation Loops (NCL)

- NCLs consist of a closed circuit, with both a source and sink of thermal energy with an elevation difference between them.
- Motion of the fluid is driven solely by density differences.
- Offer potential for Nuclear Power Plant passive cooling
  - Attractive since they can continue to provide core cooling during complete station blackout – no human/electronic action required.

Passive Heat Removal System of AP1000

- In the AP1000, the hot leg tee's off and exchanges heat with a large water filled tank (IRWST).
- This ultimately exchanges heat with the atmosphere.
- Flow returns to the cold leg to recirculate.
- Combined system claimed to provide indefinite core cooling



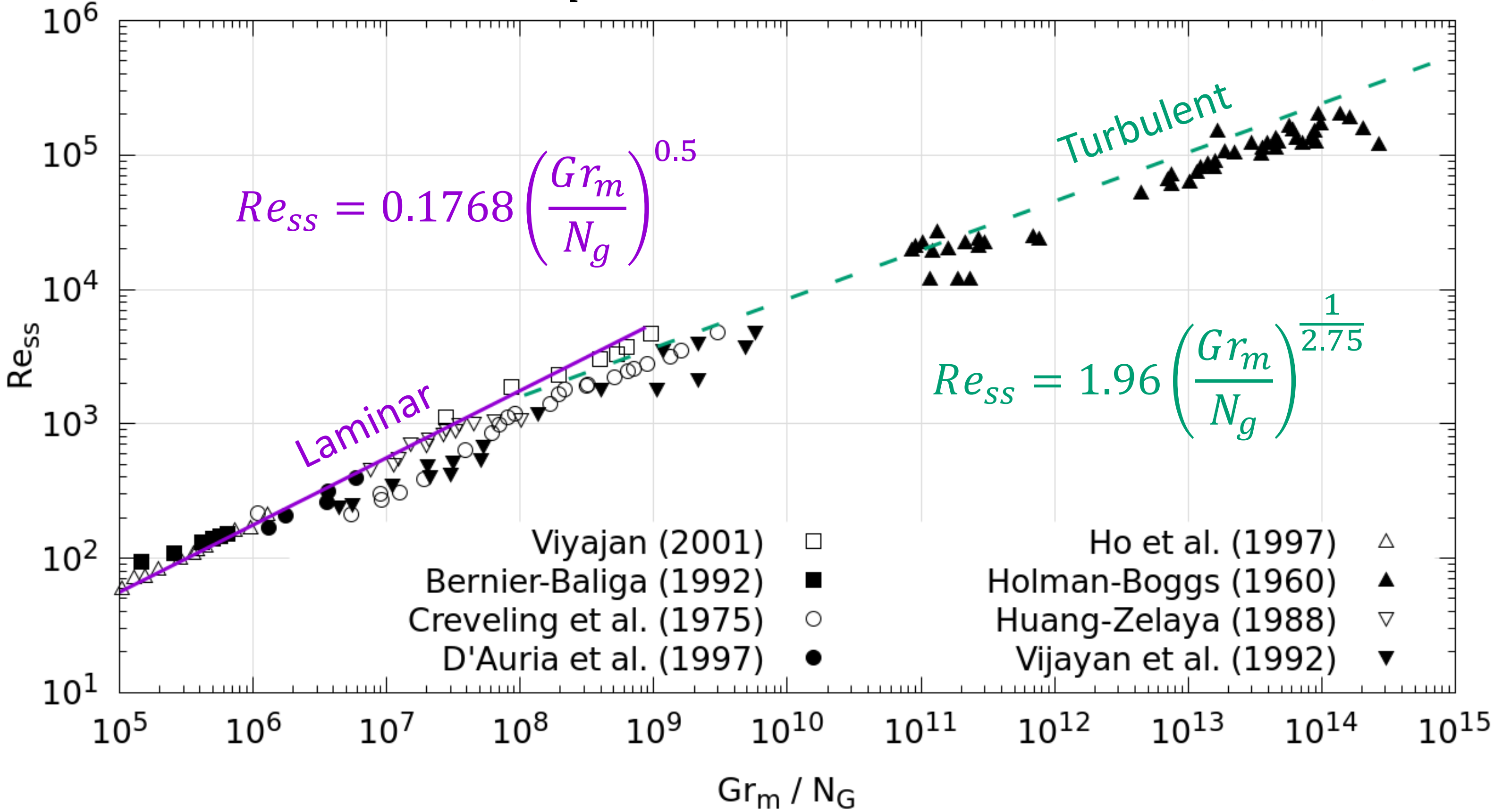
CFD for NCL

- Numerical modelling within the Nuclear industry historically relies heavily on system codes
  - Lack of fidelity translates into large uncertainties, large safety margins and increased costs (IAEA, 2009).
- Single-phase CFD codes are mature – they *can* provide fidelity but do require validation.
- Extensive literature survey revealed **no available 'CFD grade' experimental or numerical data**.
  - Most studies provide point measurements – validation for system codes – or stability analyses.
- We designed and simulated a simple 2D loop:
  - Simple enough to enable efficient RANS computations
  - Relevant enough to provide insight into the behaviour of NCL systems
- **Objective is to provide insight, demonstrate suitability of CFD approach and identify cases for further investigation (3D RANS/LES/EXP)**

Correlations

- Simple 1D analysis of momentum and energy equations reveals the governing non-dimensional parameters (Viyajan et al., 2001):

$$Gr_m = \frac{D^3\rho^2\beta g}{\mu^2}\frac{Q_h\Delta Z_c}{A\mu c_p}, \quad N_G = \frac{L_t}{D}, \quad Re_{ss} = C\left(\frac{Gr_m}{N_G}\right)^r$$

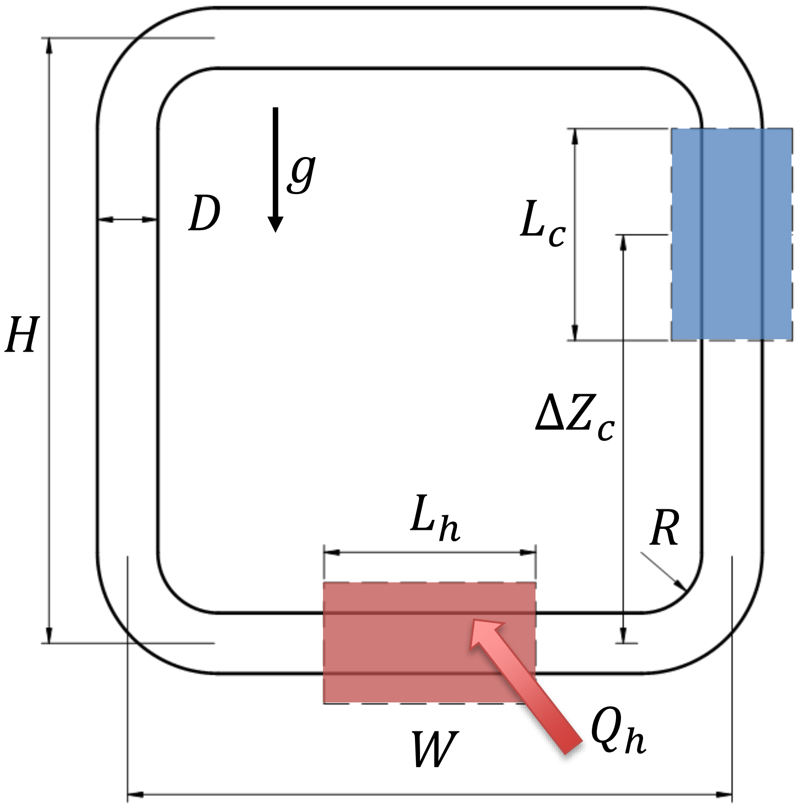


Case description

- Heater/cooler configuration:
  - **Horizontal heater at constant heat flux**
  - **Vertical cooler at constant temp.**
- Flow is specified using a modified Rayleigh number:

$$Ra_m = \frac{D_h^3 \rho \beta g Q_h \Delta Z_c}{\alpha \mu^2 A_r c_p}$$

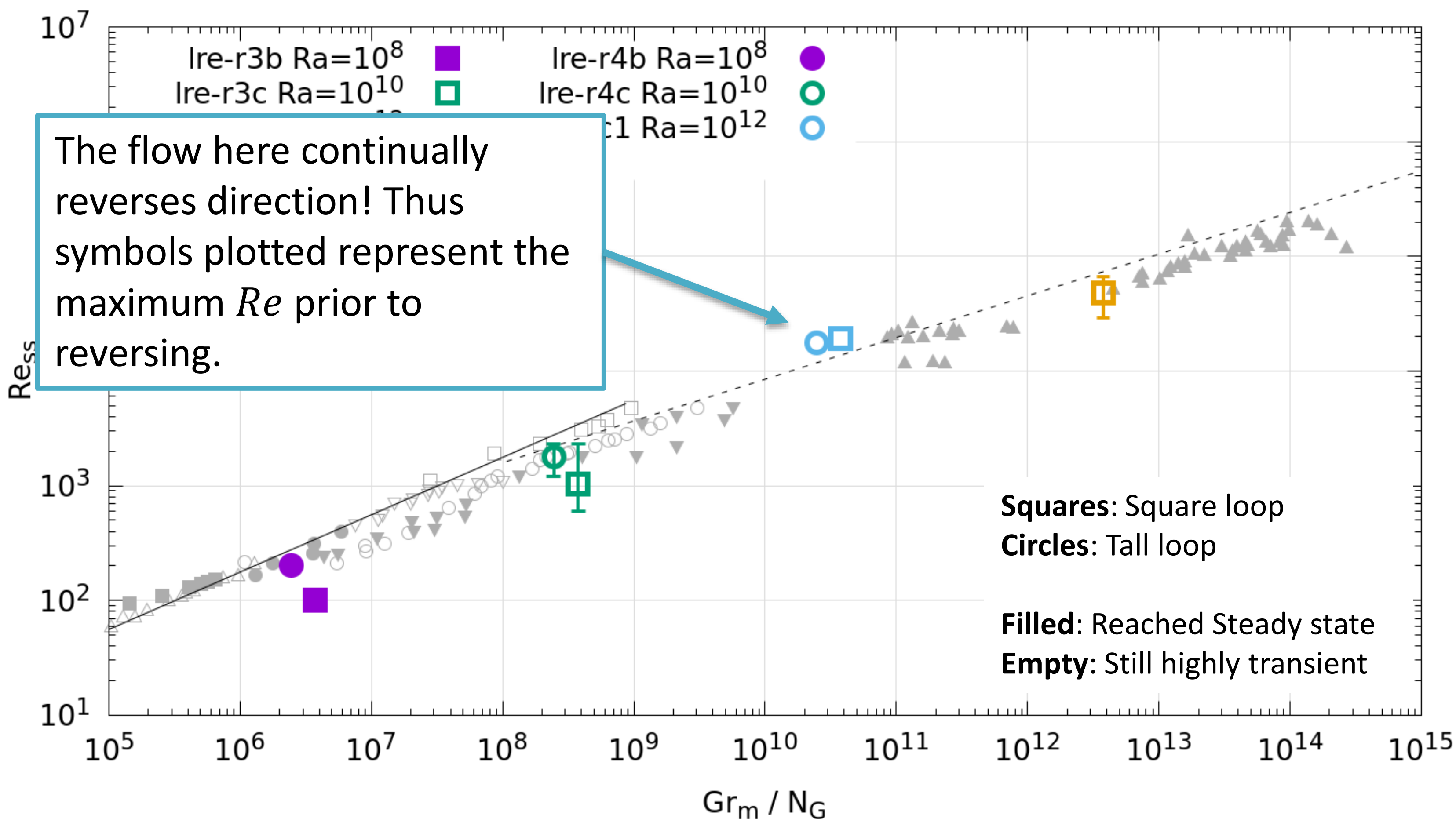
- Explore parameter space
  - **2 loop aspect ratios** $\boldsymbol{H/W = 1, 1.5}$
  - $\boldsymbol{Ra = 10^8,\ 10^{10},\ 10^{12},\ 10^{14}}$
- Initial conditions
  - **Still fluid, temperature close to cooler**



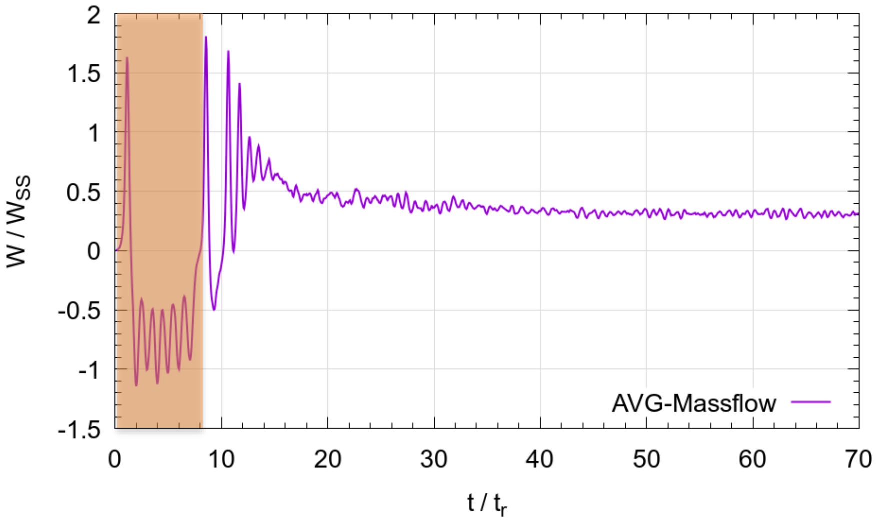
- Turbulence modelled with low-Re k-epsilon model.
- Non-dimensional time step estimated from loop circulation time
  - **Aim to resolve one circulation in ~10,000 time steps**

Results: Overview

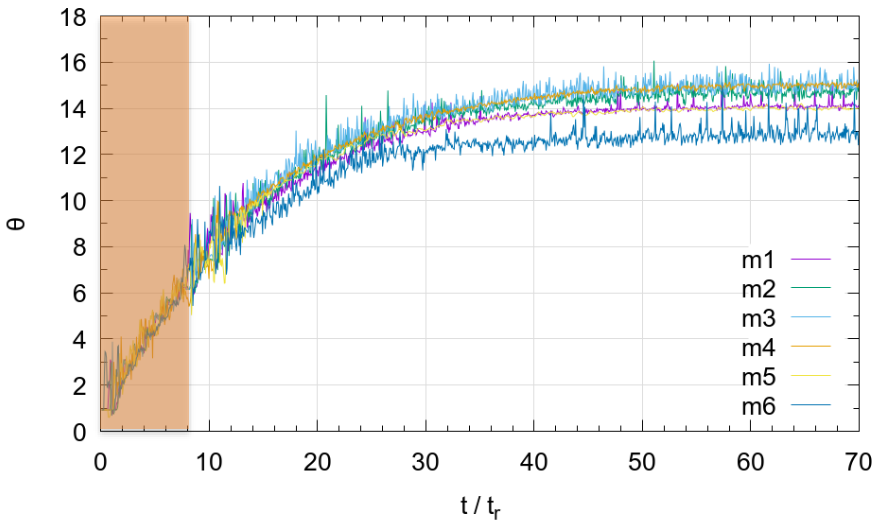
- Lower Ra have reached a statistically steady state – reasonable agreement with correlations (despite being 2D).
- Others have not – bars indicate range of Reynolds numbers exhibited so far…



Results: $Ra = 10^8$ Monitor history



Non-dimensional mass flow rate

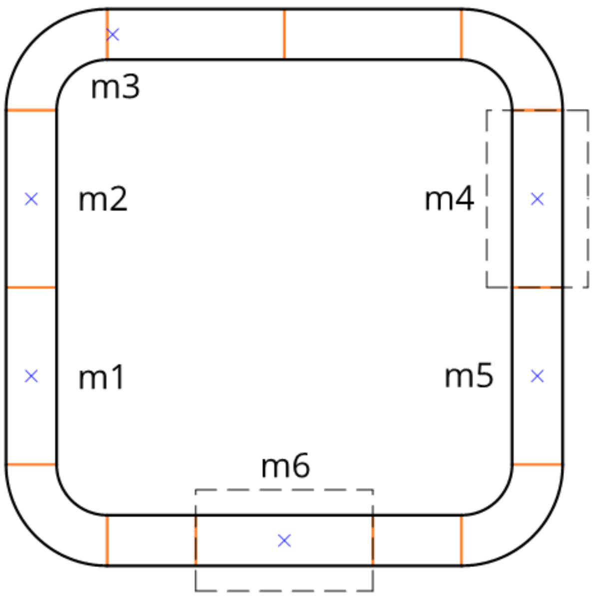


Non-dimensional temperature

- Thermal field establishes density differences
- Flow initially circulates clockwise…
- Then reverses and circulates anti-clockwise… before reversing again
- Does eventually appear to reach a statistically steady state

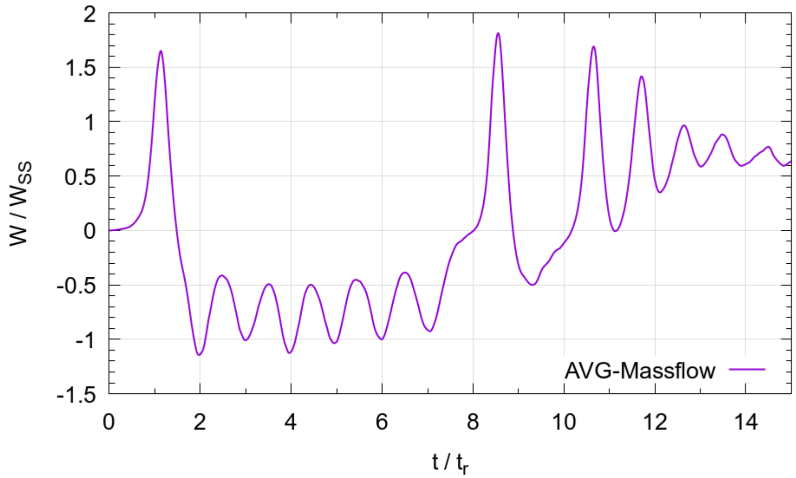
$$t_r = \frac{\rho V_t}{W_{ss}}$$

$$\theta = \frac{T - T_c}{(\Delta T_h)_{ss}}$$

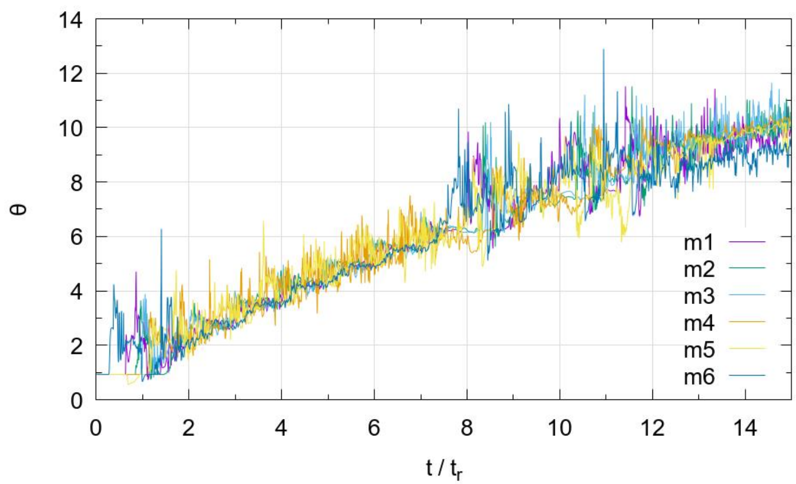


Monitor locations

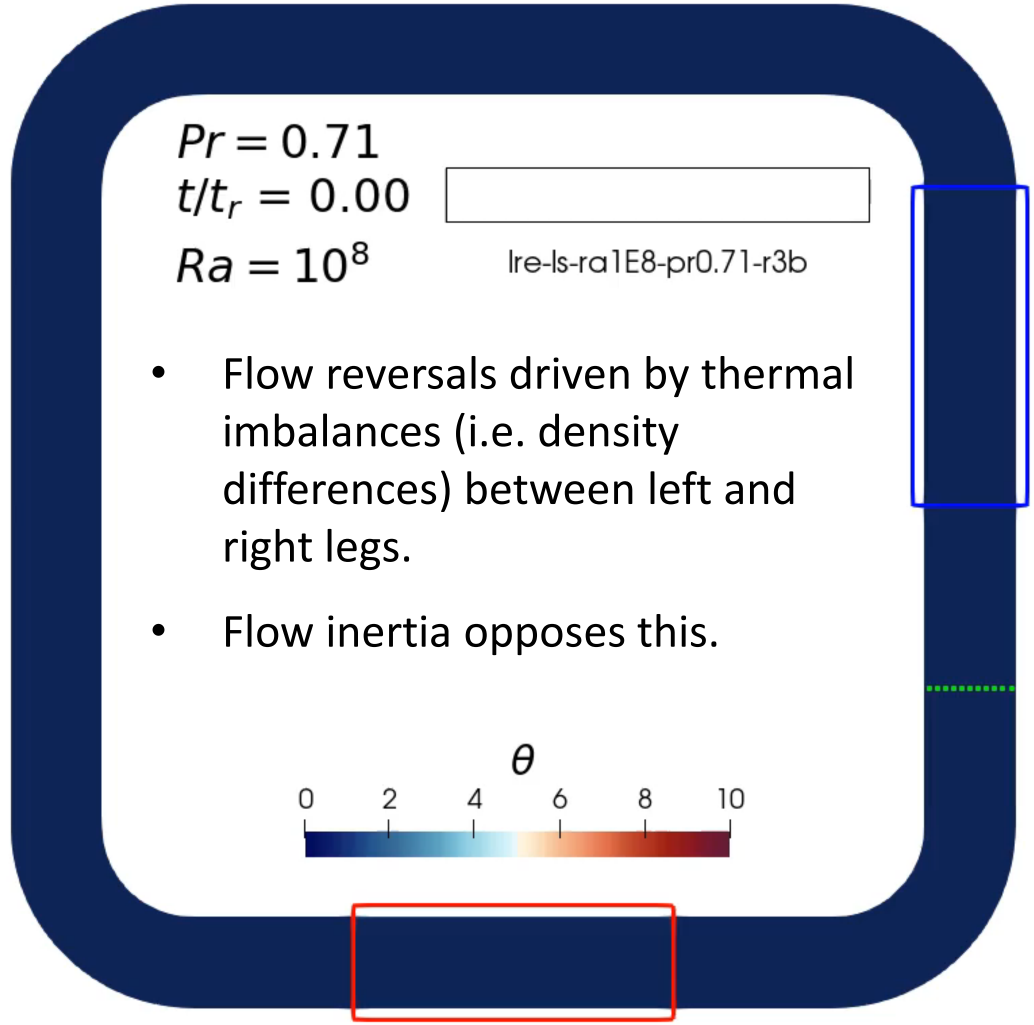
Results: $Ra = 10^8$ Startup



Non-dimensional mass flow rate



Non-dimensional temperature

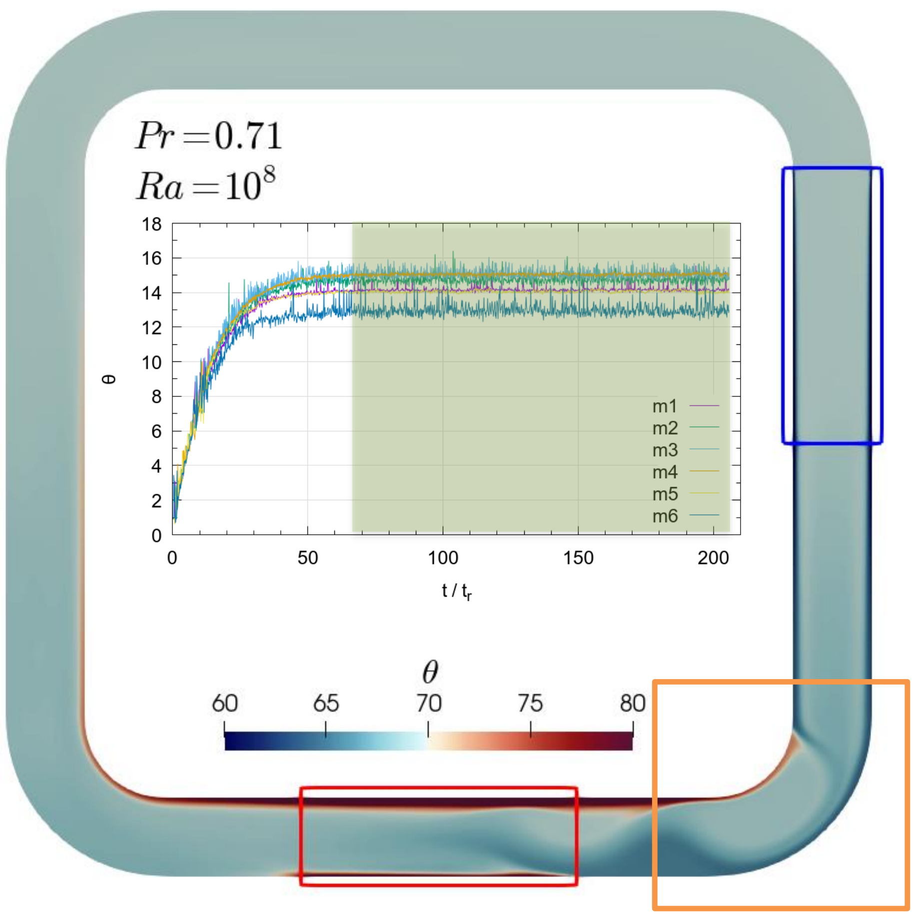


- Flow reversals driven by thermal imbalances (i.e. density differences) between left and right legs.
- Flow inertia opposes this.

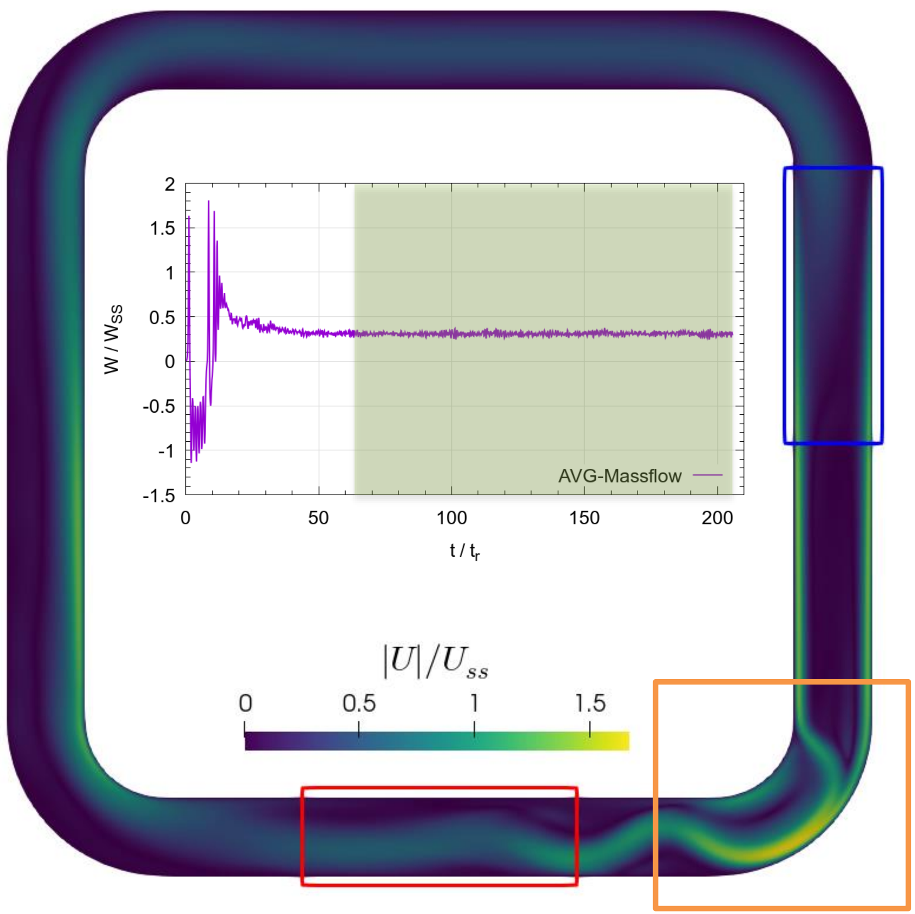
Non-dimensional temperature

Results: $Ra = 10^8$ Steady state

- Hot fluid 'leaking' up right leg impinges with cooler sinking fluid – causes downward flow to 'divert' around.

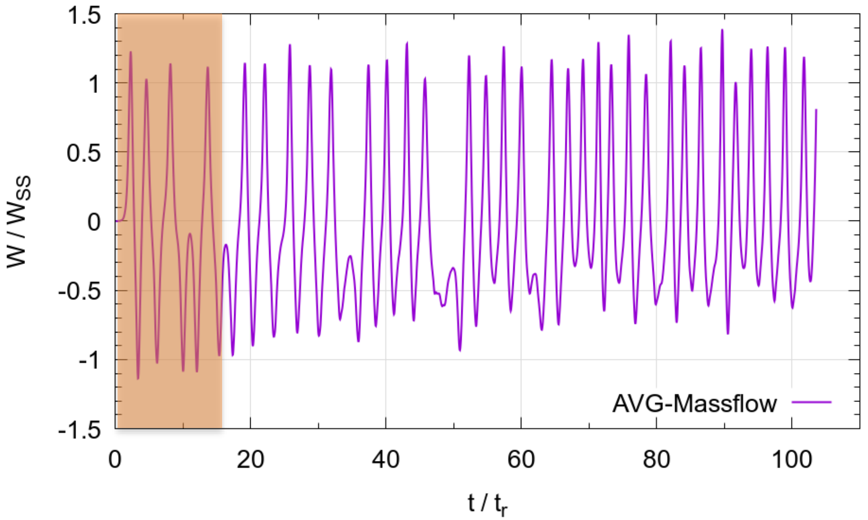


Non-dimensional temperature



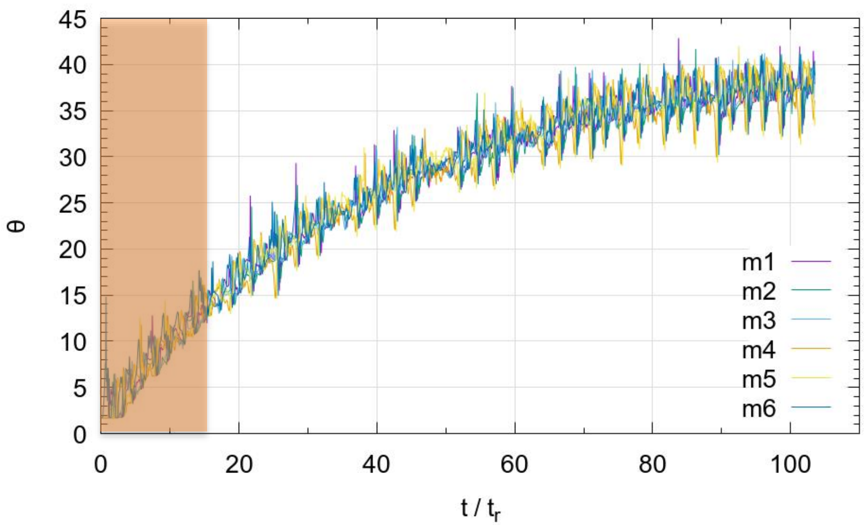
Non-dimensional velocity magnitude

Results: $Ra = 10^{12}$ Monitor history



Non-dimensional mass flow rate

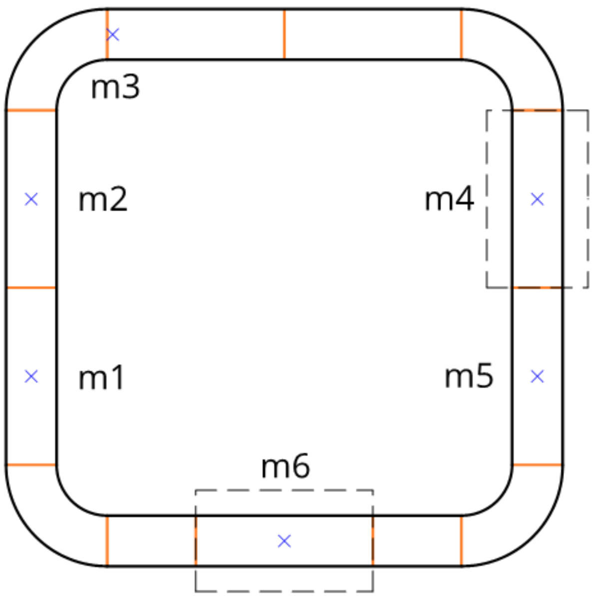
- At the higher Rayleigh number ($Ra = 10^{12}$) the flow continues to reverse periodically.
- Reversals occasionally fail to fully complete.
- Amplitude of oscillations doesn't seem to be significantly reducing.



Non-dimensional temperature

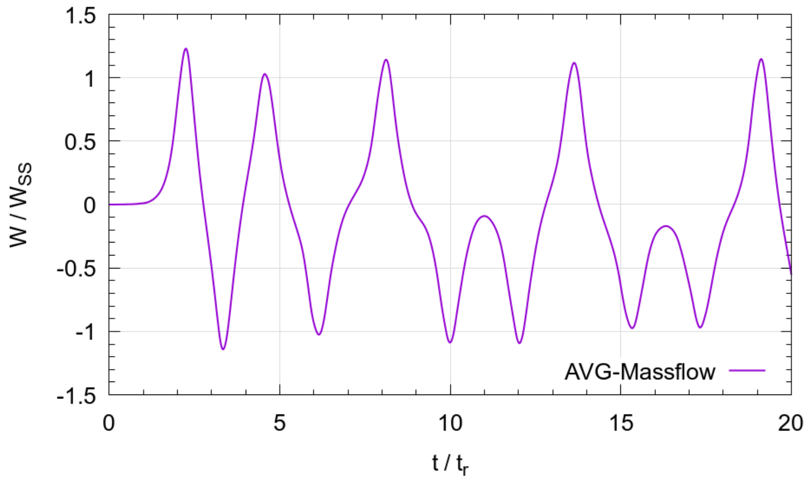
$$t_r = \frac{\rho V_t}{W_{ss}}$$

$$\theta = \frac{T - T_c}{(\Delta T_h)_{ss}}$$

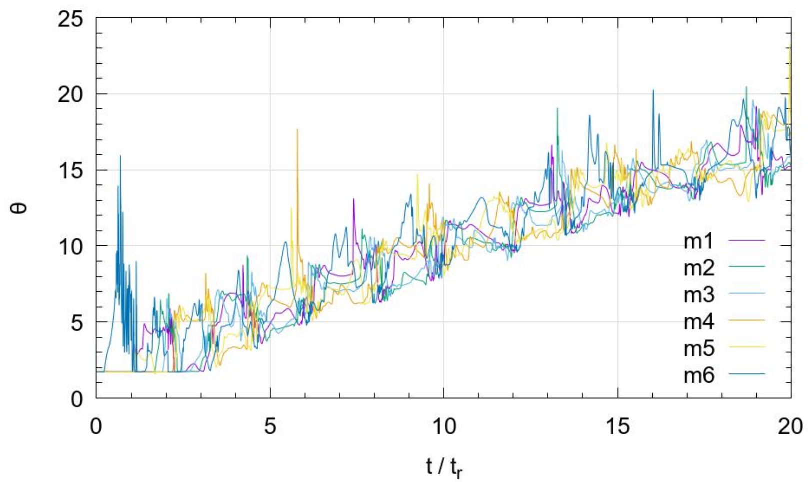


Monitor locations

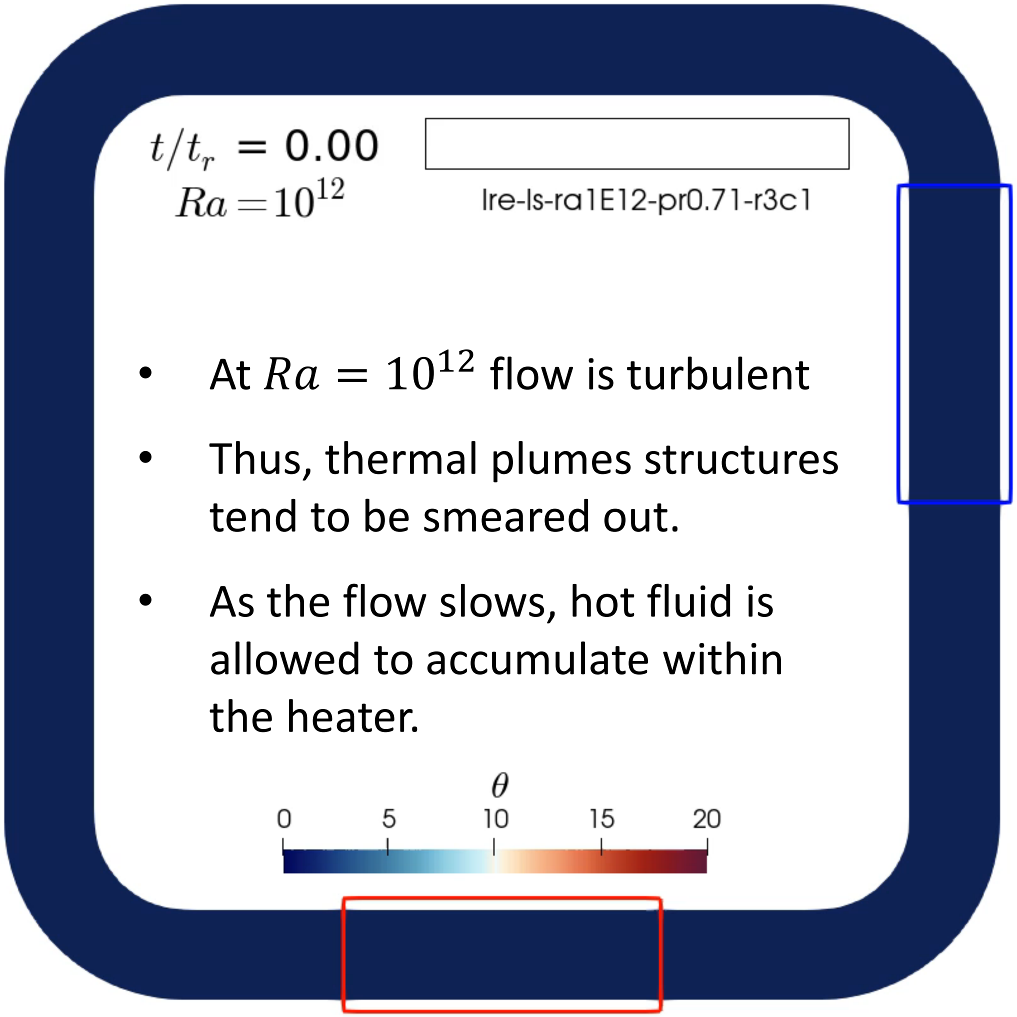
Results: $Ra = 10^{12}$ Startup



Non-dimensional mass flow rate



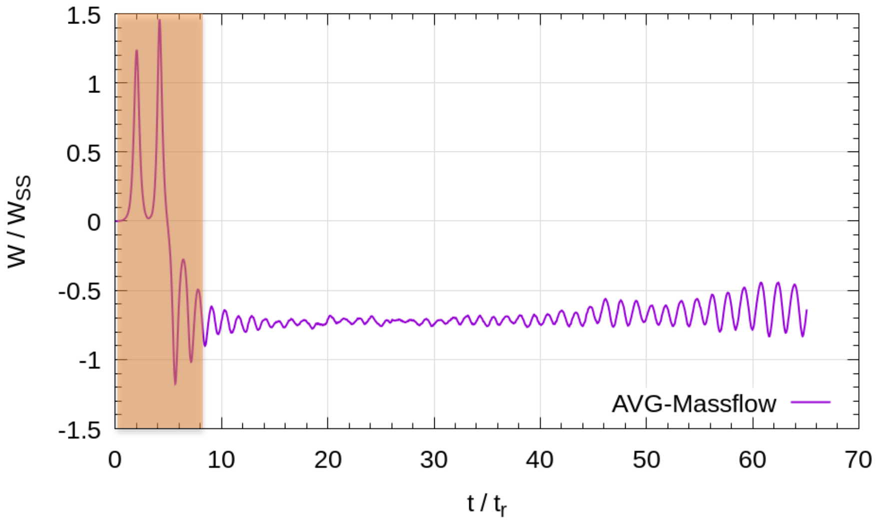
Non-dimensional temperature



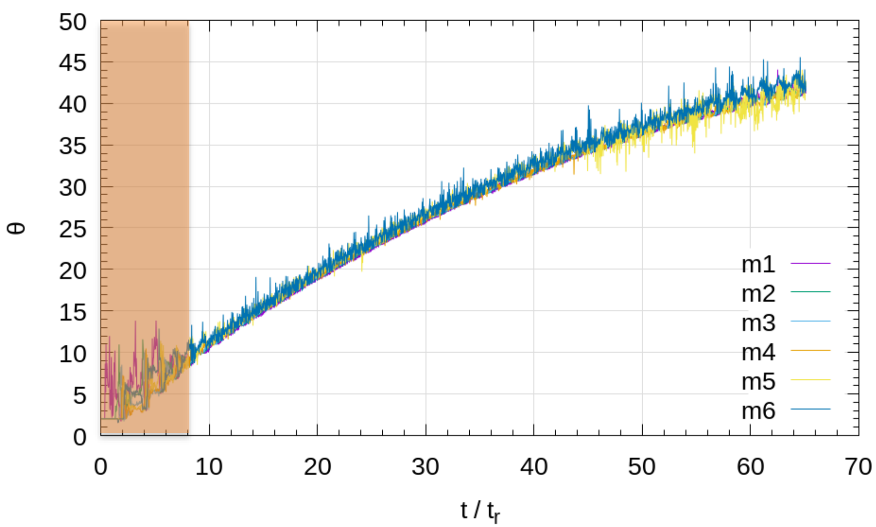
- At $Ra = 10^{12}$ flow is turbulent
- Thus, thermal plumes structures tend to be smeared out.
- As the flow slows, hot fluid is allowed to accumulate within the heater.

Non-dimensional temperature

Results: $Ra = 10^{10}$ Monitor history

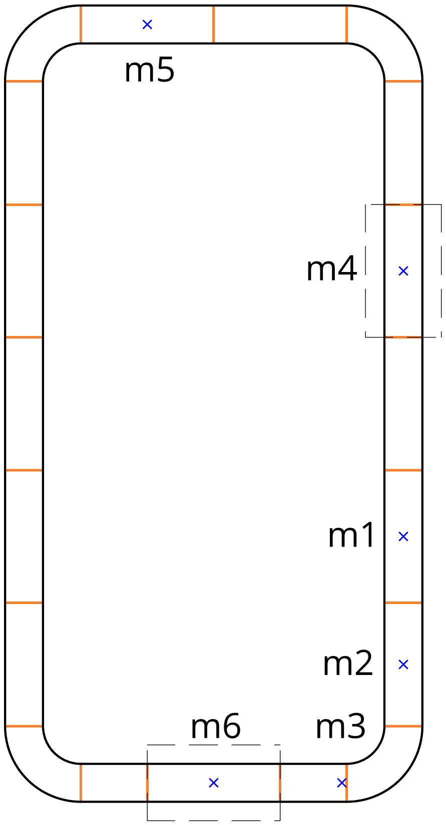


Non-dimensional mass flow rate



Non-dimensional temperature

- Tall loop at $Ra = 10^{10}$ initially doesn't reverse, but does almost stop.
- Flow then reverses, seems to settle.
- Flow currently travelling anti-clockwise!
- Thermal equilibrium doesn't demand a particular flow direction.
- Buoyant force in cooler has to overcome flow inertia.

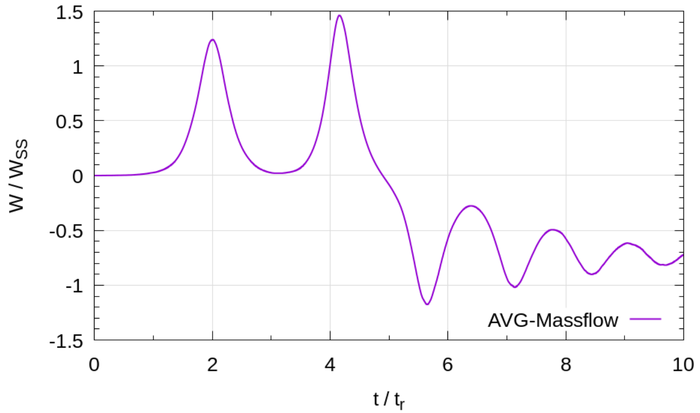


Monitor locations

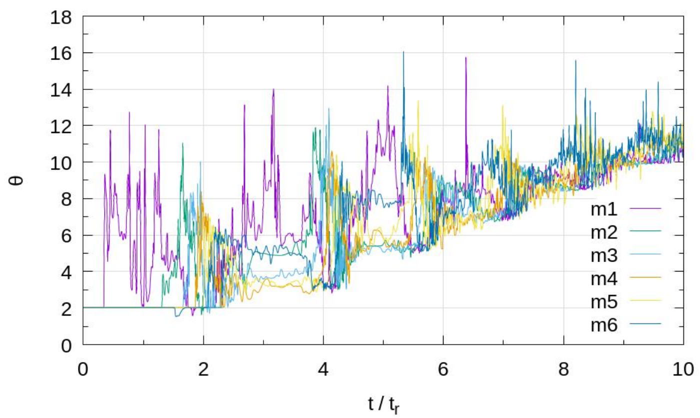
$$t_r = \frac{\rho V_t}{W_{ss}} \qquad \theta = \frac{T - T_c}{(\Delta T_h)_{ss}}$$

Results: Ra^{10} Startup

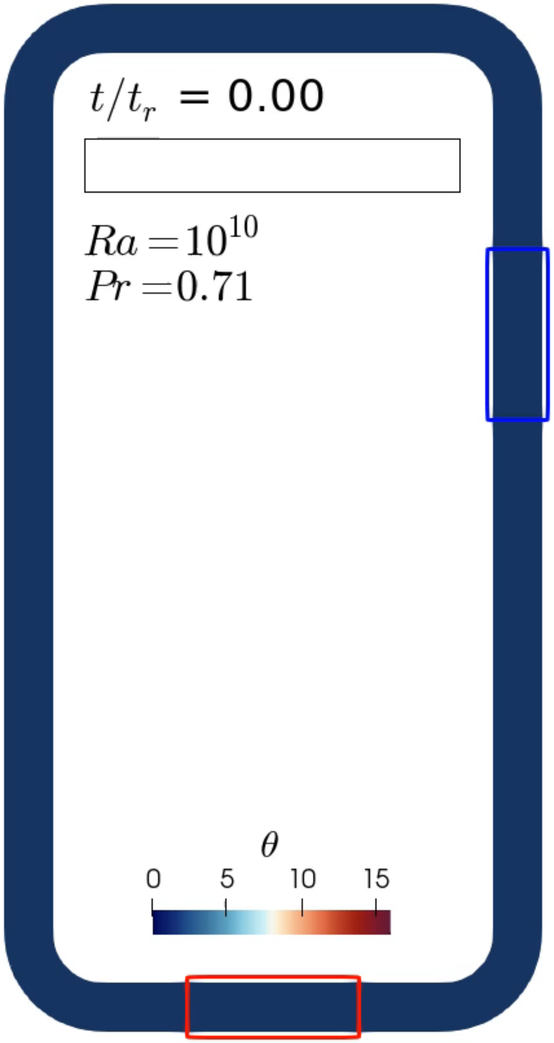
- Complex transient interactions between thermal plume structures.



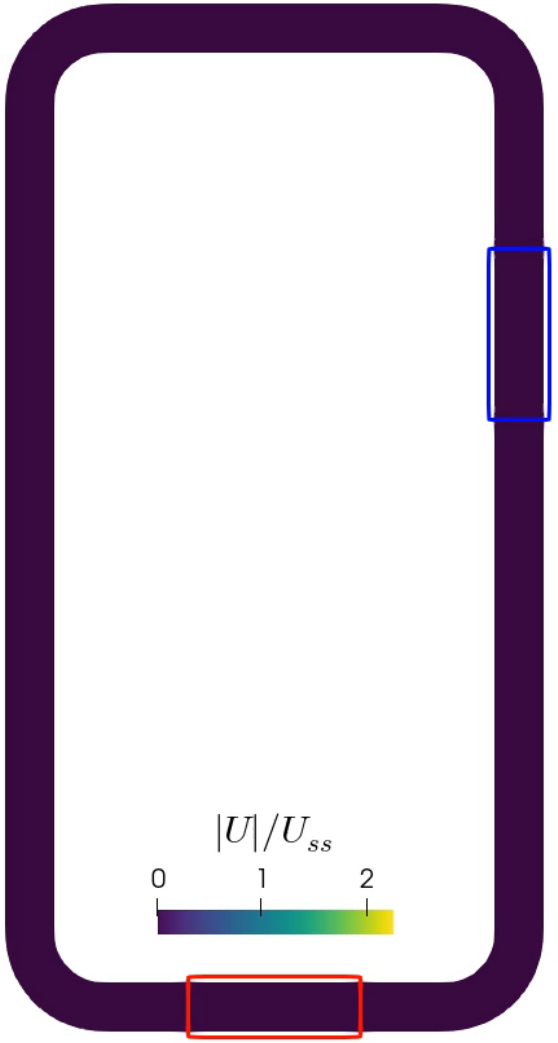
Non-dimensional mass flow rate



Non-dimensional temperature



Non-dimensional temperature



Non-dimensional velocity magnitude

Summary

- **Numerical simulations of Natural Circulation Loops predict significantly complex transient behaviour.**
  - Thermal and momentum fields strongly coupled.
  - Both localized complexities and overall system instabilities observed.
  - URANS seems to be effective at predicting this … **but needs validation**.
- **Initial thermal imbalance can lead to significant initial transients**
  - Mass flow rates tend to oscillate and even reverse direction
  - Bulk temperature slowly rises as thermal imbalance eliminated.
- **Computations at higher Rayleigh numbers ongoing…**
  - How long for?! Some may not reach (or have) a statistically steady solution.
  - Lots of data still to be analysed. PhD student at UoM currently working on this.
- **Many options for further study.**
  - Select cases to be solved in 3D and using LES – higher fidelity, will aid validation and guide model development.
  - Different heater/cooler configurations – some potentially more stable.
  - Influence of more nuclear relevant geometries (more bends, valves, etc).

Rod bundle boil-off

Preliminary 2D computations

Case description

- Rod-bundle boil off
  - Loss of primary coolant circulation leads to pool type boiling within fuel assemblies.
  - Two-phase mixture front develops and travels down the bundle.
  - Exposed rod surfaces can experience dangerous increases in temperature (CHF).
- Multiphase CFD a potentially powerful prediction tool.
- Limited published experimental data
- **Objective is to conduct in-house boil-off experiments and numerically simulate them with recent s-o-t-a two-phase boiling models.**
- Currently a 'Work In Progress'

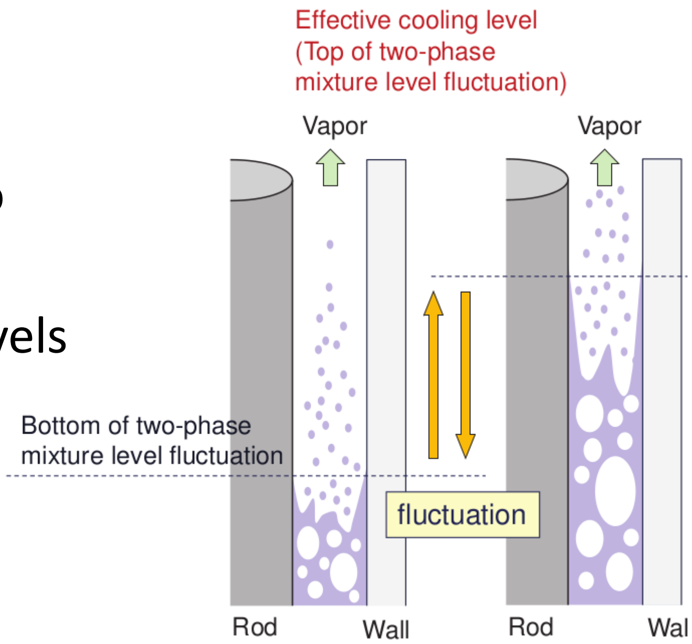
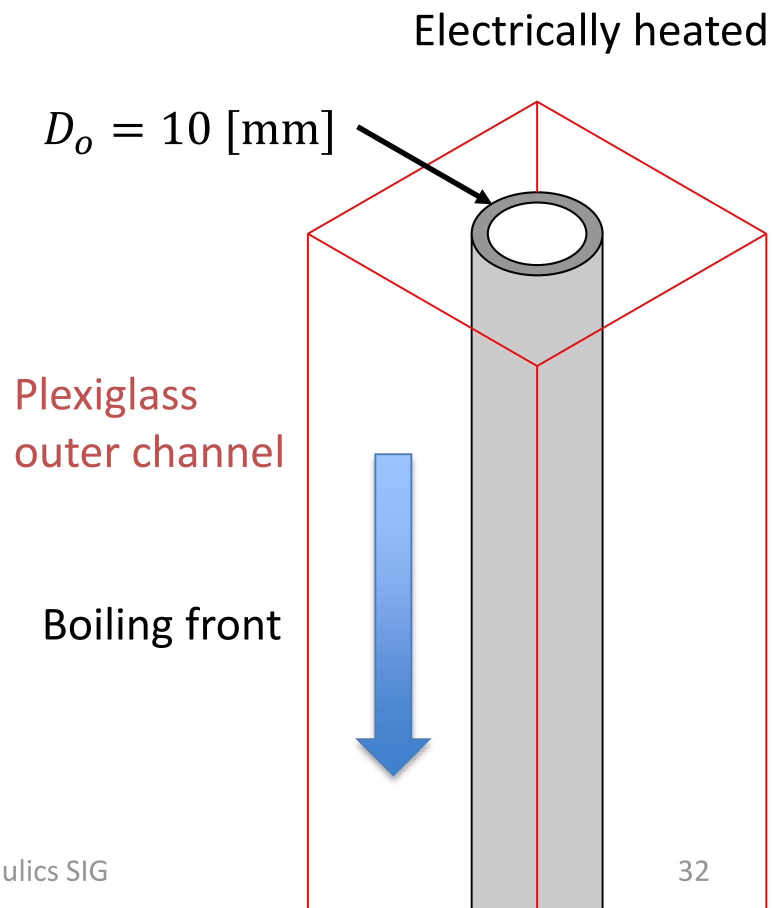


Image from Arai et al., 2015

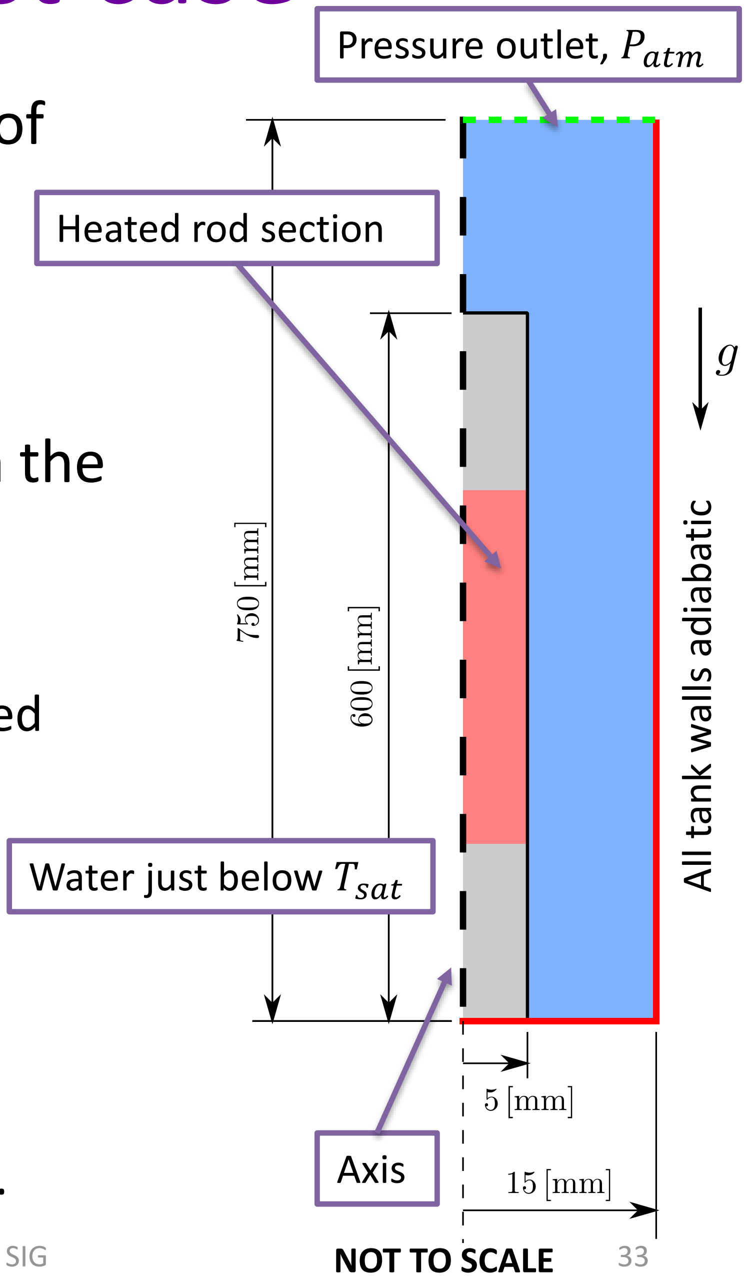
In-house experiments

- Conducting our own boil-off experiments at UoM
  - Single rod enclosed in clear square channel.
  - Fill the channel with water, apply a heat flux (electrical heating) to the tube and boil it dry.
- Data measured
  - Capture liquid-vapour boiling front morphology with high resolution-high speed cameras.
  - Void fraction (pressure transducers)
  - Rod wall temperature along axial length (thermocouples)
- Simplified test piece configuration
  - 1 rod, no spacer grids.
  - Easier numerical benchmarking.



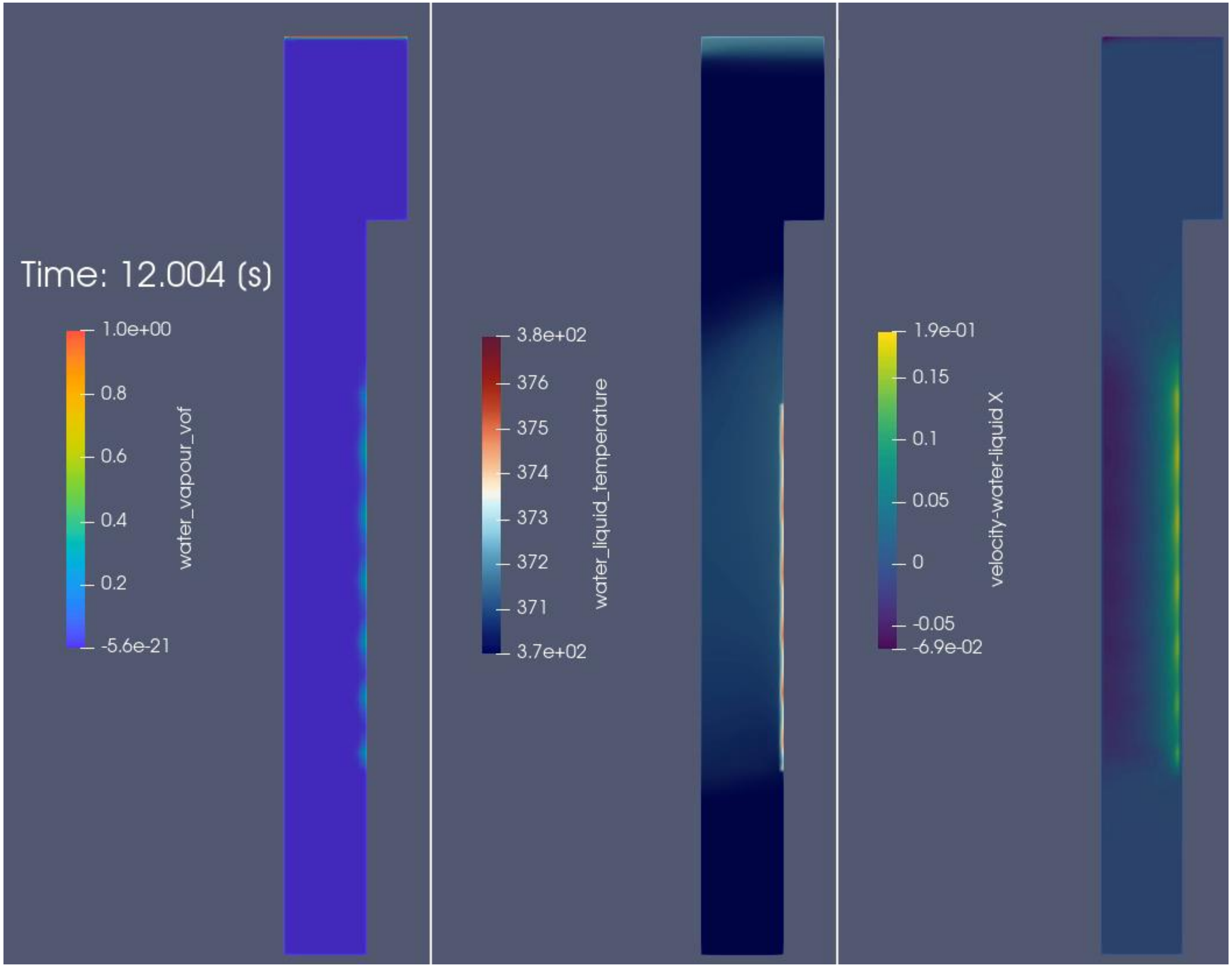
Preliminary test case

- Preliminary 2D axisymmetric version of experiment.
- Uniform heat flux applied to middle section of the rod.
- Pressure outlet positioned away from the rod to reduce boundary effects.
- Solved using ANSYS FLUENT
  - Eulerian two-fluid approach with extended RPI wall boiling model
  - $k-\varepsilon$ applied to mixture.
  - Water properties vary as per IAPWS97.
- Aim is to see if we can reproduce a boiling mixture front.
  - Explore impact of various RPI submodels.



Preliminary Results

- Vapour generation along heated rod.
- Condenses once it reaches cooler fluid above.
- Bulk liquid temperature rising but not yet reached saturation temperature.
- Convective cells established.
- Computations ongoing.



Summary & Future work

- Conducting tandem experimental and CFD investigations of rod-bundle boil off.
- Both aspects are currently in progress.
- Preliminary results demonstrate potential of the numerical modelling approach.
- Data provided by the experiment will allow rich quantitative and qualitative analysis – should help drive model development.

Thank you!