‘Plumbing’, or Thermal hydraulics in Nuclear Fission and Fusion

Dr Michael Bluck

Imperial College

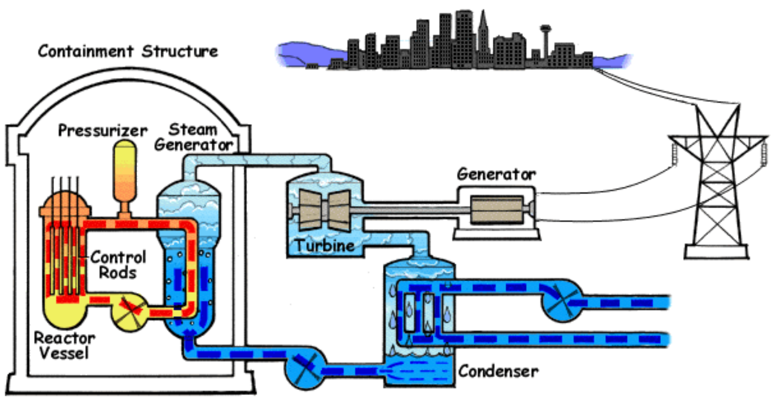
Introduction

- Role of TH in nuclear
  - Coolability
  - Normal operation
  - Accident scenarios
- Issues in fission
  - TH Analysis; Systems codes & correlations, CFD
  - Boiling, critical heat flux, natural circulation
  - Bridging the scales
- Issues in fusion
  - Tokomaks
  - Fusion blankets
  - Magnetohydrodynamics

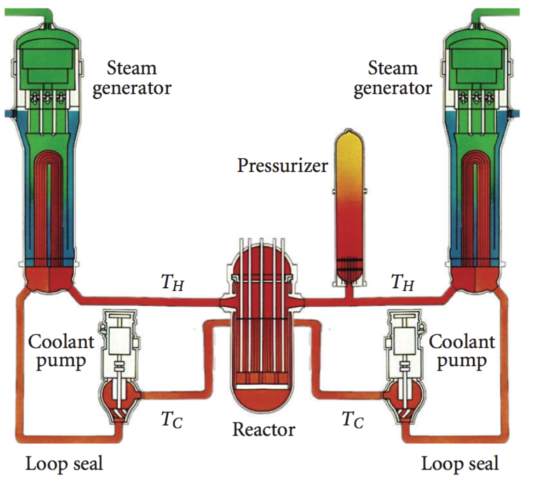
Role of TH in nuclear: Coolability

- The core of a nuclear reactor converts atomic binding energy to heat
- Heat is converted to electrical energy by means of (typically) steam turbines
- Inter alia, we need a means to convert heat into steam – **thermal hydraulics**
  - Efficiently (higher temperatures, improved heat transfer,…)
  - Reliably (backup systems, natural circulation,…)
- Maintaining the extraction of heat from the core is vital – **coolability**
  - Normal operation
  - Scheduled or unscheduled transients
  - Accident scenarios
- Failure to maintain coolability is catastrophic
  - Chernobyl, Fukushima, etc
- Regulator requires coolability to be established in all design scenarios

Role of TH in nuclear: Normal Operation



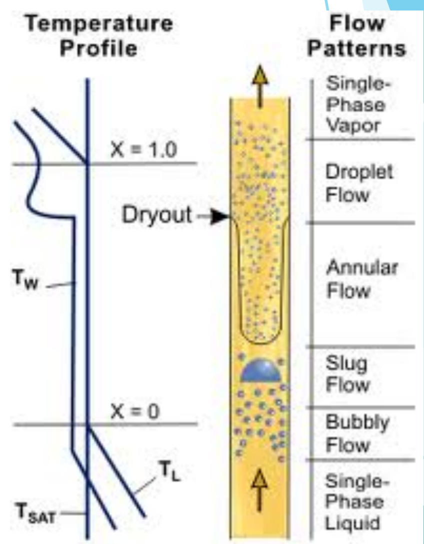
By U.S.NRC. - http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html, Public Domain



- Typical PWR
- Two loop design
- Primary loop
  - Pressurized to 15 Mpa
  - Tin ~ 550K, Tout ~590K
- Power generation limited by ability to remove core heat

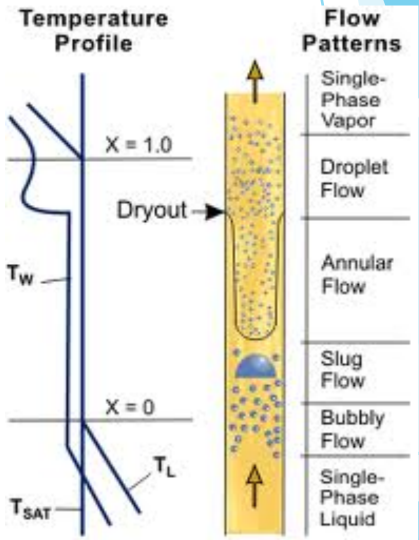
Issues in fission: Accident scenarios

- Coolability may be lost due to:
  - Pump or power failure
  - Structural failure (blockages)
  - Loss of coolant accident (LOCA)
  - Anything else anyone can think of….
- Heat generation does not stop immediately
  - 7% decay heat after shutdown
- Cooling must me re-established
  - Emergency backup power, pumps
  - Emergency core coolant systems (ECCS)
  - Natural circulation



Issues in fission: Accident scenarios

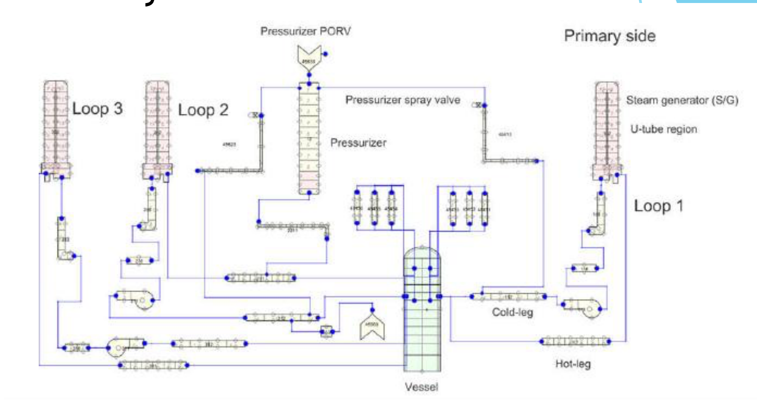
- In normal operation the flow in a core channel is (largely) single phase liquid, homogeneous and turbulent
- In accident scenarios:
  - Single phase…
  - Subcooled nucleate boiling – bubbly flow
  - Saturated nucleate boiling – slug flow
  - Annular film flow & droplet entrainment
  - Single phase vapour
- Leading (at some point) to dryout, critical heat flux (CHF), boiling crisis
- **The ability to predict onset of dryout is the most important job in fission thermal hydraulics**
- At this point the wall temperature shoots up due to the poor heat transfer
  - Fuel bin ballooning due to internal pressurization
  - Risks rupture and contaminant release
  - Produces hydrogen due to steam-Zircalloy reaction
- Prediction is extremely difficult due to the complexity of the flow and heat transfer



Issues in fission: TH Analysis

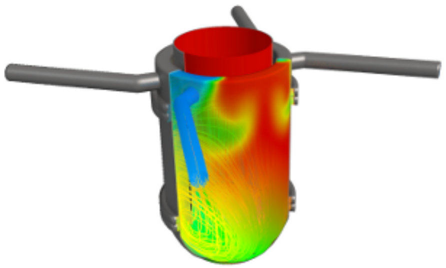
- How do we establish coolability?
- Experiments (costly and difficult)
- TH prediction via computational tools
  - Systems codes
  - CFD

Systems codes: Plant scale

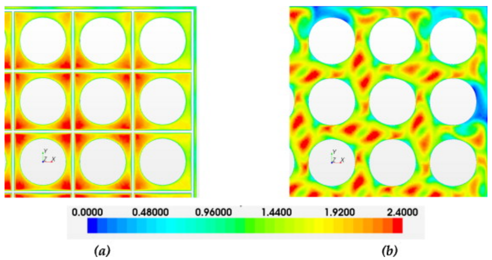


Detail

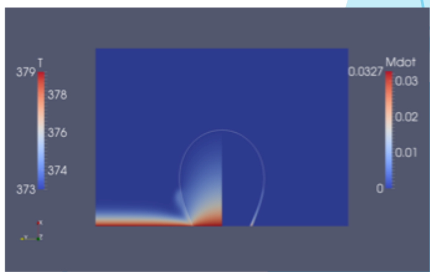
<Plant scale



Component scale



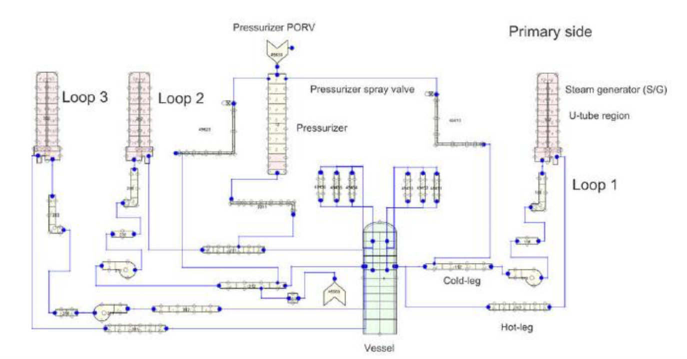
Microscale



Effects

Issues in fission: Systems codes

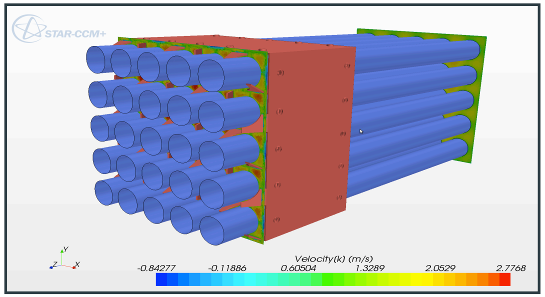
- Systems codes are and have been (since 1950s), the workhorse of nuclear thermal hydraulics
- Eg RELAP5, CATHARE, TRAC/TRACE
- Can capture dynamics of the whole reactor
- Widely accepted by regulators
- They necessarily lack detail on local flow and heat transfer conditions

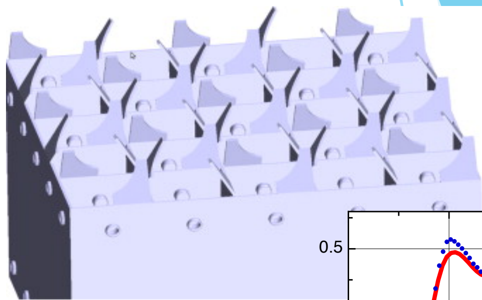


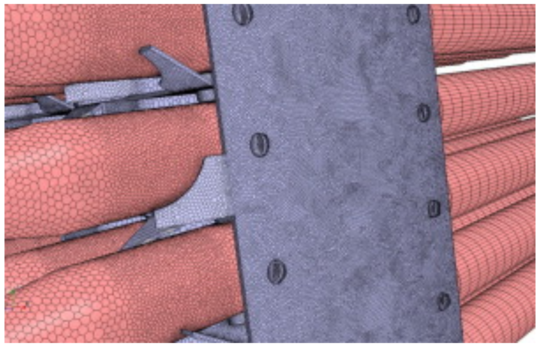
- Flow is modelled as a 1D network
  - 3D effects are entirely ignored (averaged)
  - Mass, momentum and energy are conserved within the network
  - Hydrodynamic effects (wall drag, pressure drop) and heat transfer is accounted for by **phenomenological** models
  - These are realized as correlations for eg. Friction factor, Nusselt number (heat transfer coefficient) as functions of Re, Pr, flow regime, and CHF (eg Chen correlation).
  - Includes component scale phenomenological models of eg. Dryers, condensers, pumps, etc
- Phenomenological models obtained from experiment, CFD or analytical methods

Issues in fission: CFD for Single phase turbulent flows

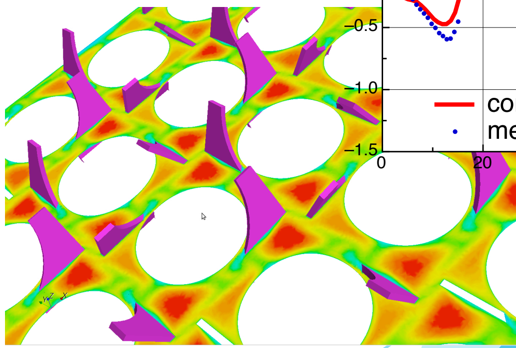
- Acceptable for normal operation studies
- Typically RANS or increasingly LES
- Reasonable accuracy for reasonable CPU resource for component scale models
- These results are from an OECD-NEA blind benchmarking exercise
- Multiphase flows (with heated walls) are much more uncertain & unreliable – they still employ phenomenological models to take account of boiling

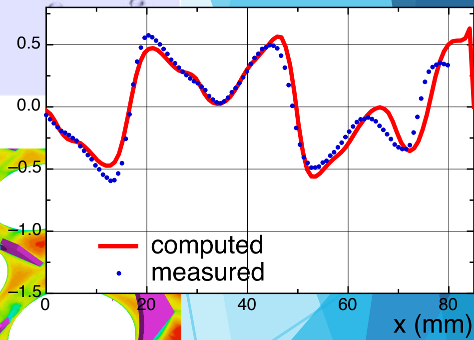






Details of the mesh. The vane region and the region of interest downstream of the grid are meshed more finely.



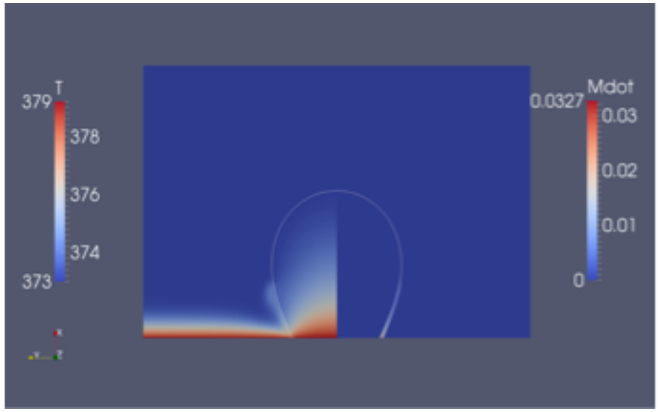


Cross-sectional profile of the axial velocity, *w* (m/s)

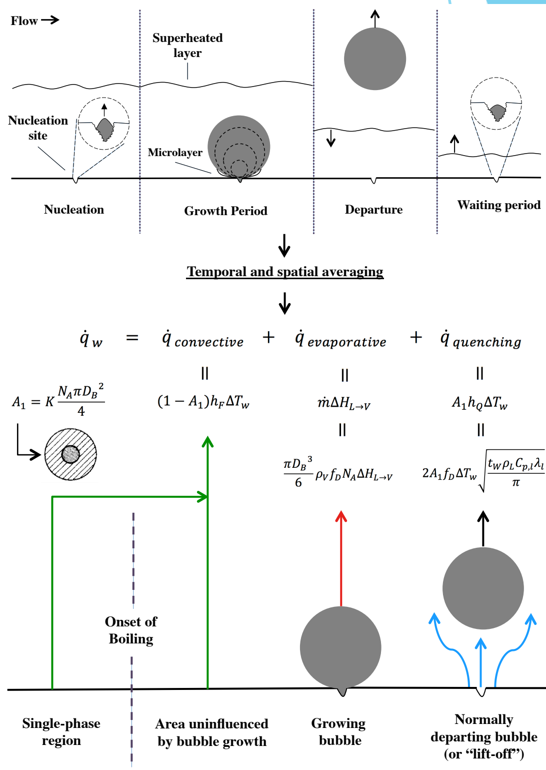
N. Cinosi, S.P. Walker, M.J. Bluck, R. Issa **CFD simulation of turbulent flow in a rod bundle with spacer grids (MATIS-H) using STAR-CCM+,** Nuclear Engineering and Design, Volume 279, 2014, 37–49. http://dx.doi.org/10.1016/j.nucengdes.2014.06.019

Issues in fission: Multiphase flows, boiling, transitions

- During accident scenarios in particular, a complex multiscale, multiphase evolution of flow up the channel is seen
- Originates in bubble formation, growth and departure
- Makes important contributions to the heat transfer process
- Fundamental studies of boiling processes
- CFD – interface tracking methods
- Development of phenomenological models (for CFD and SCs)



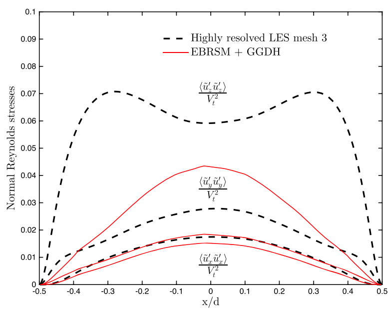
G Giustini, Nuclear Engineering Group, Mechanical Engineering Dept. Imperial College



R Thakrar, Nuclear Engineering Group, Mechanical Engineering Dept. Imperial College

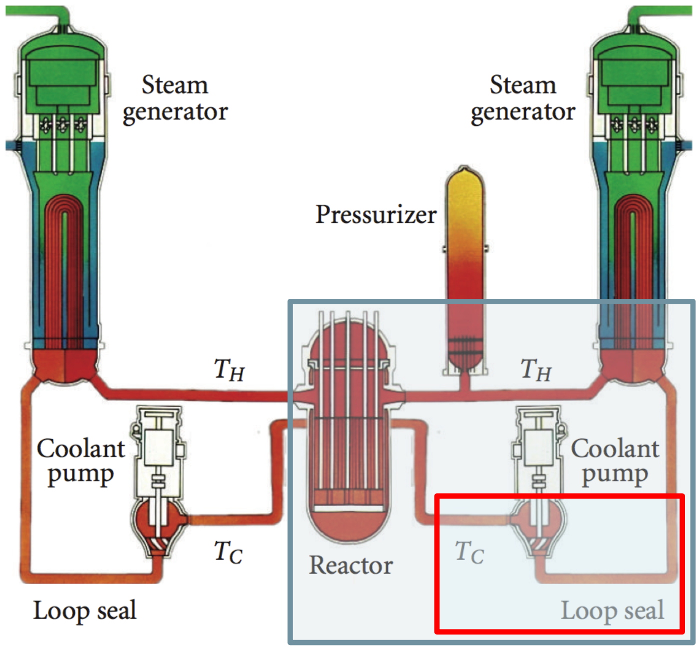
Issues in fission: Natural Circulation

- A ubiquitous solution in modern nuclear reactor designs
- Can be quite unstable
- Challenging for typical RANS turbulence models in CFD:

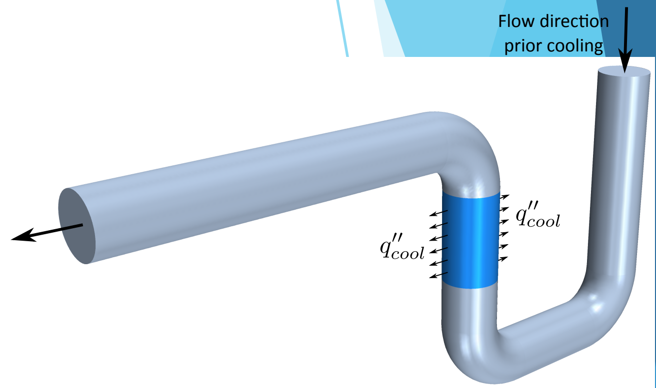


Sebilleau, F., R. I. Issa, and S. P. Walker. "Analysis of Turbulence Modelling Approaches to Simulate Single-phase Buoyancy Driven Counter-current Flow in a Tilted Tube." *Flow, Turbulence and Combustion* 96.1 (2016): 95-132.

Engineering problem



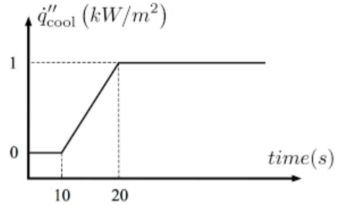
CFD model

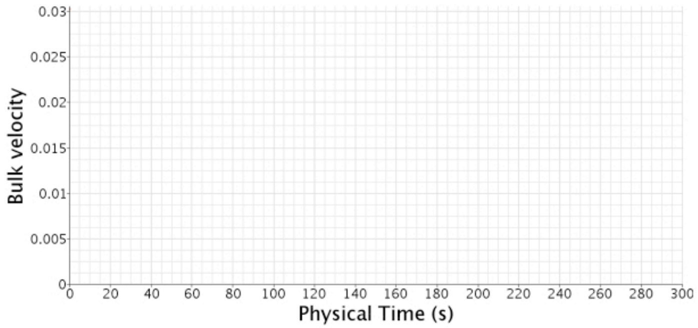


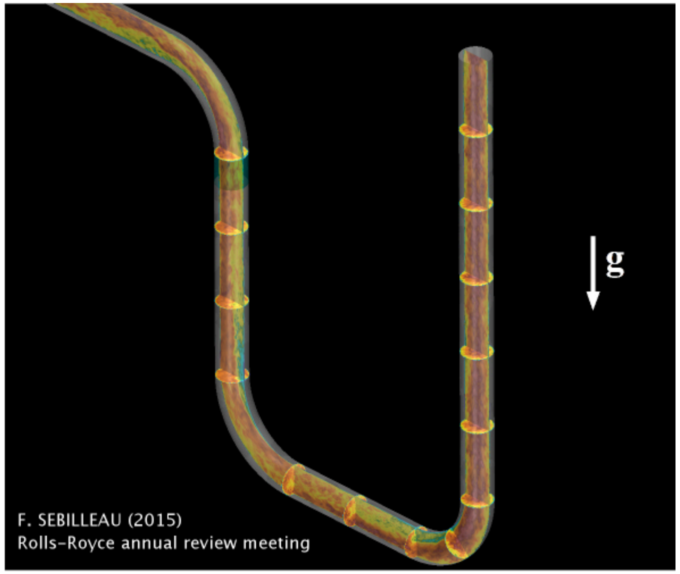
- Constant pressure drop applied to model initial natural circulation (difficult to justify in reality…)
- Heat losses modeled by uniform heat flux cooling

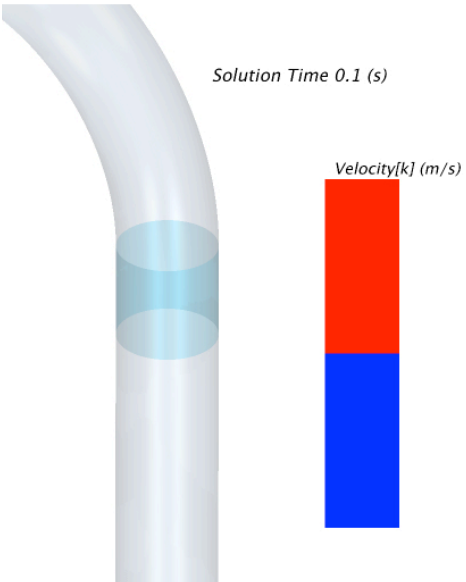
The model embodies all the complexity of the physics needed for turbulence model validation

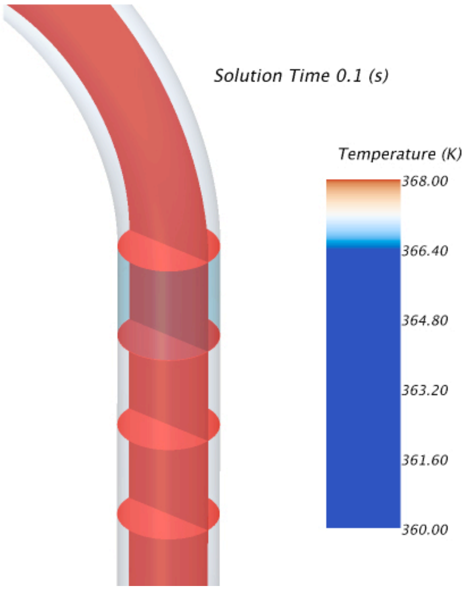
$$\mathrm{Re} = 20000$$
$$T_{ref} = 368\mathrm{K}$$
$$P_{ref} = 1\mathrm{bar}$$

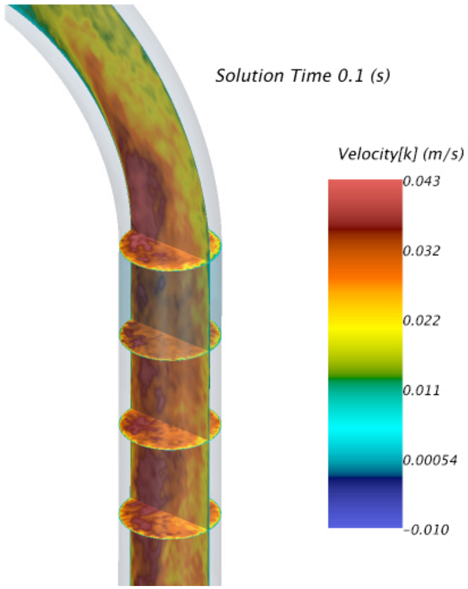








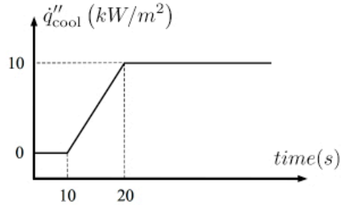


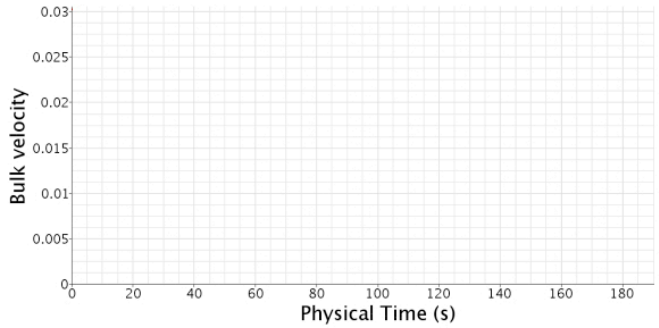


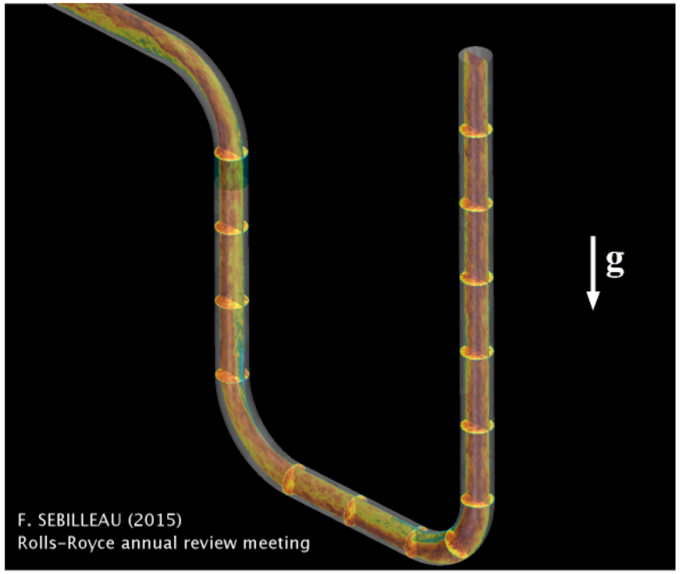
$$\mathrm{Re} = 20000$$

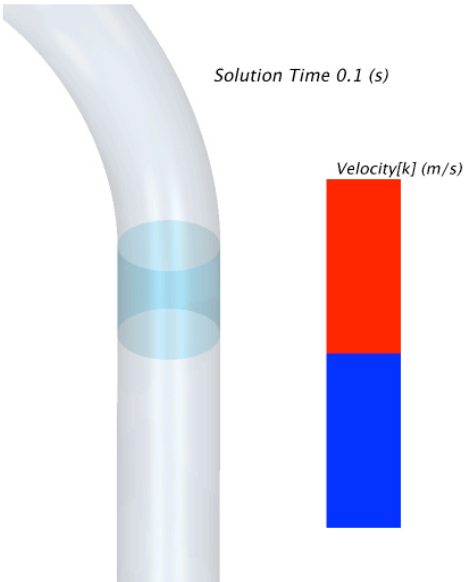
$$T_{ref} = 368\mathrm{K}$$

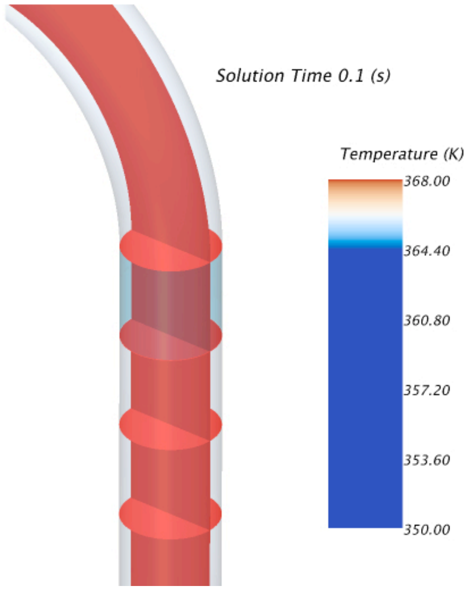
$$P_{ref} = 1\mathrm{bar}$$

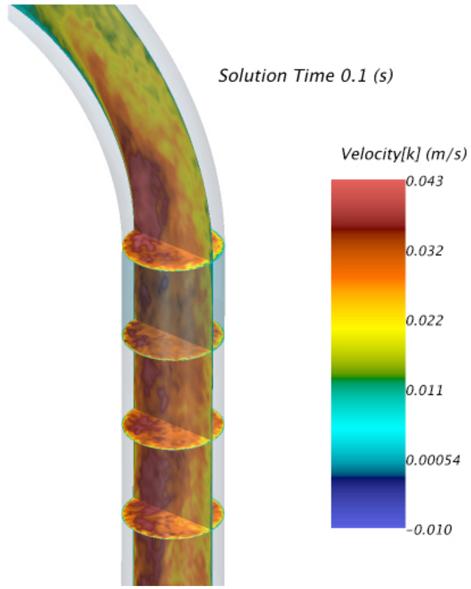








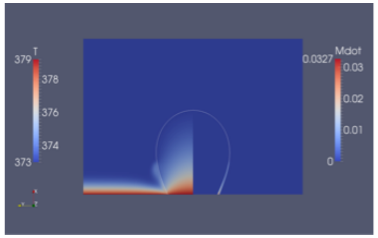




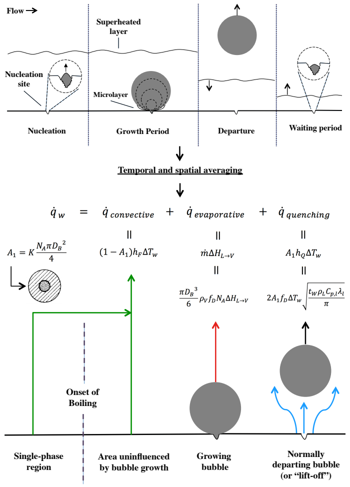
Issues in fission: Bridging the scales

- Systems codes model entire plant scenarios
  - Fast, but can lack detail
  - Rely on phenomenological models of wall friction, heat transfer, interphasic heat and mass transfer, CHF
- CFD can model single phase turbulent flows and heat transfer in components quite (if not very) well
  - This is generally the case in normal operation
  - Effective full-plant models beyond envisaged HPC capabilities
  - Multiphase flows are much more challenging; boiling, CHF in particular
  - Use of phenomenological models for sub-scale effects such as boiling
- Accident scenarios lead to multiphase, multiscale challenges
- How do we bridge the scales?

Issues in fission: Bridging the scales

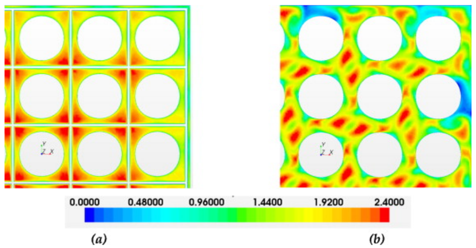


Microscale CFD boiling studies



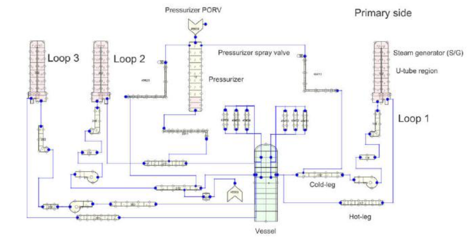
experimental boiling studies

Improved phenomenological models



Multiphase component scale CFD

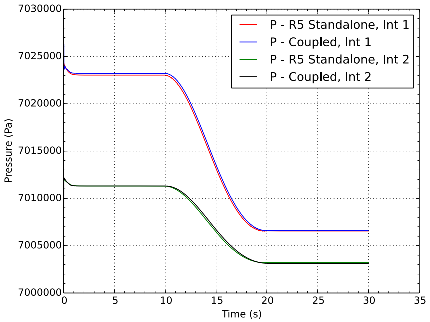
Code coupling

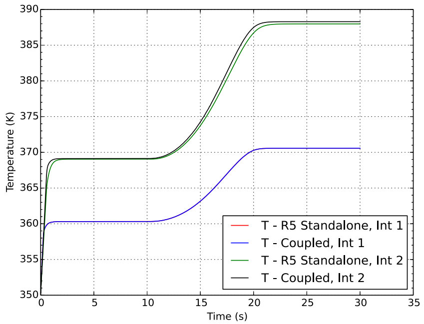


Plant scale: Systems codes

Issues in fission: Code coupling

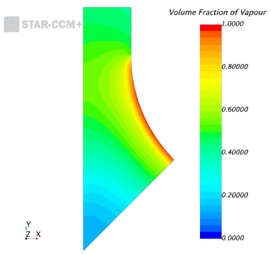
- Need to bridge the plant and component scales
- Code coupling: Use of Systems Codes where appropriate & CFD where detail is needed
- Eg. At Imperial: STAR-CCM+ (CD-Adapco) and RELAP5-3D (INL)
- Challenges:
  - Ensuring conservation of mass, momentum and energy
  - Entrance regions and numerical head loss at interfaces; profile reconstruction

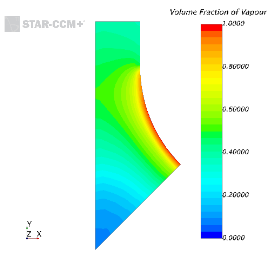




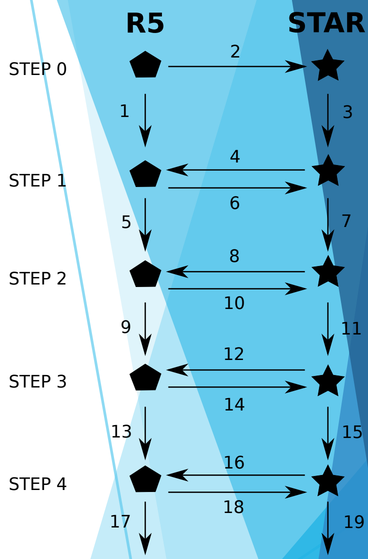
AP Palazzi, MJ Bluck, S Lo, ‘A Coupled RELAP5-3D/STAR-CCM+ Simulation for the Calculation of Friction Factor in Pipes’, Proceedings ICAPP 2014, ANS, pp. 1323 - 1329.

Standalone





Interface 1



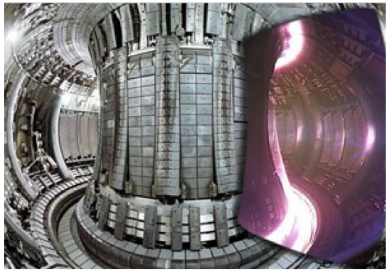
Conclusions

- Despite developments in computational resource, accurate prediction of CHF is still years away
- Experimental programmes are required to develop our understanding and validate numerical predictions
- We have focused on issues central to thermal hydraulics, but these influence and are influenced by many related fields, eg.
  - CRUD deposition & chemistry – axial offset anomaly, heat transfer effects
  - Flow induced corrosion
  - Flow induced vibration

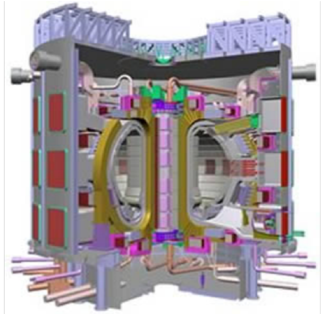
- …and now fusion....

Thermal hydraulics in fusion reactors

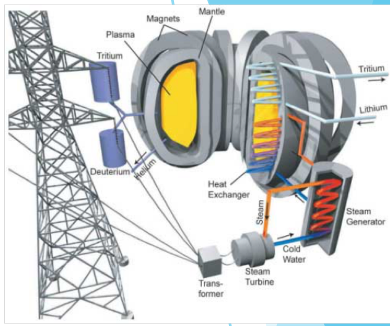
- A ‘holy grail’
- Most focus has been on plasma confinement and control
- Going forward, focus is shifting to supporting technology:
- Heat removal
- Tritium generation



JET - 1983 (CCFE)
16MW in 1991

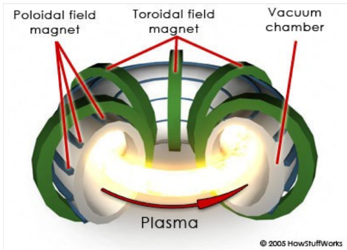


ITER - (Building started 2013)
500MW ~2025

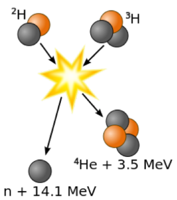


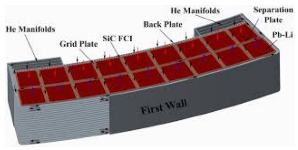
DEMO
3GW ~2035-2050

- Deuterium + Tritium fused in a hot plasma (100x10^6 K)
- Plasma contained by powerful (10T) magnetic fields
- Heat removed + tritium produced by a ‘blanket’



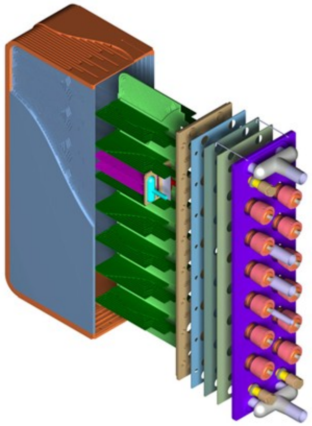
Deuterium-tritium fusion" by Wykis - Own work, based on w:File:D-t-fusion.png. Licensed under Public Domain via Commons



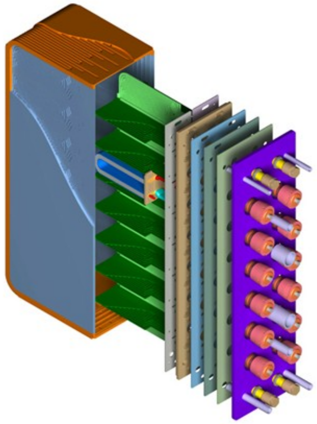


Issues in fusion: fusion blankets

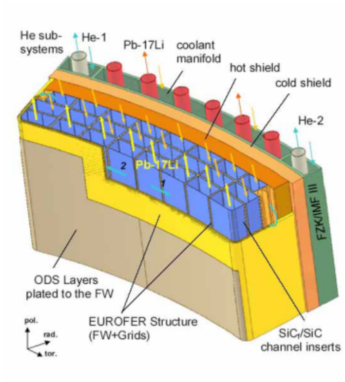
- Numerous blanket concepts have been considered:



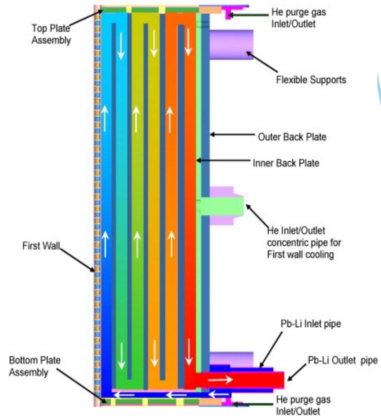
EU HCLL



EU HCPB



US DCLL



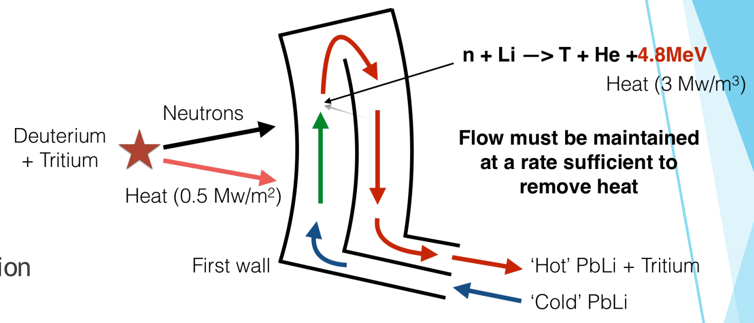
Indian LLCB

(Figures courtesy IDOM, Matta UCLA; IoPR Bhat.)

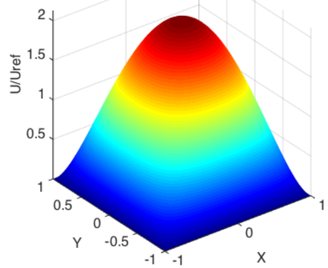
- No breeding blankets have been built – just CAD models
- ITER Test Blanket Modules will provide first experimental data
- Concepts share common features with fission – coolant in flow channels, manifolds, complex junctions.
- Modelling is crucial for future blanket development

Issues in fusion: Magnetohydrodynamics

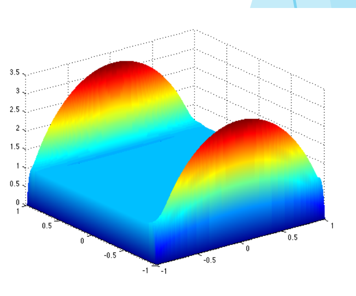
- As in fission, energy is extracted via a coolant flow along ducts and pipes
- In addition:
  - Coolant is lead-lithium eutectic
  - Tritium generation & transport
  - Blanket is bathed in an intense (~5T) magnetic field
  - Profound magneto-hydrodynamic effects; turbulence suppression
- Entire blanket systems code models
  - Use of systems code approach to model entire blanket and ancilliary components
  - Need additional phenomenological models appropriate to MHD
- Magnetohydrodynamic CFD
  - Needed for complex geometries, flow is often laminarized
  - Coupling to a magnetic field
  - Much less well developed than non-MHD
  - Need new turbulence models



Flow profiles in a rectangular duct



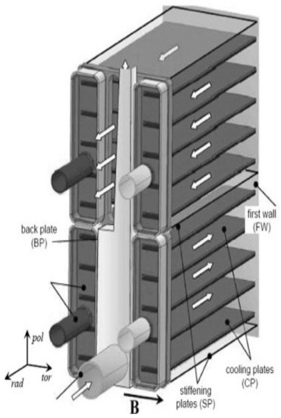
non-MHD



MHD

Magneto-hydrodynamic effects: Heat transfer

Figure 1 from Dimitris Dimopoulos and Nikos Pelekasis
2012 Fluid Dyn. Res. 44 031405



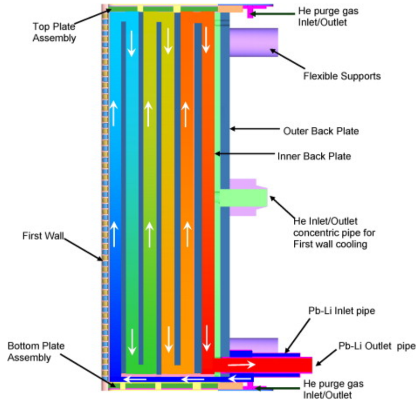
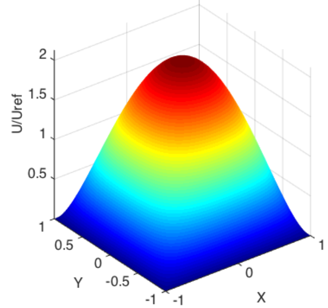


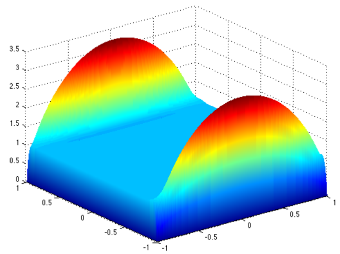
Figure 2.1: Cross sectional schematic of the Indian Lead Lithium Ceramic Breeder (LLCB) DEMO blanket concept [3]

Hartmann number is the ratio of magnetic forces to viscous forces. High magnetic fields correspond to high Hartmann number

Effect on flow profile



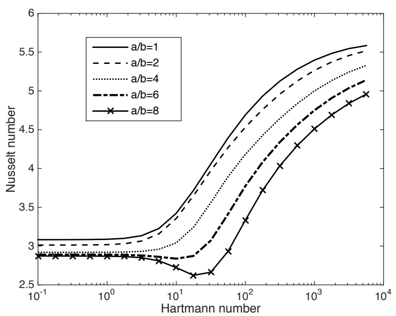
non-MHD



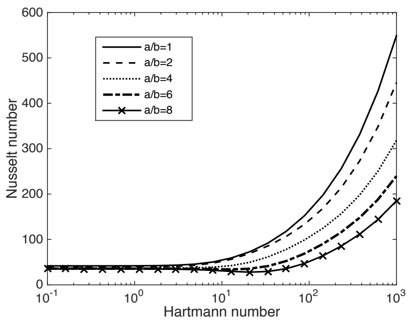
MHD

Heat transfer improves with increase magnetic field (B). Volumetric heat removal can be orders of magnitude greater than surface heat removal at high B

Bluck, Michael J., Michael J. Wolfendale, and Andrew J. Marquis. "An analytical solution to the heat transfer problem in Shercliff flow." *International Journal of Heat and Mass Transfer* 86 (2015): 542-549.



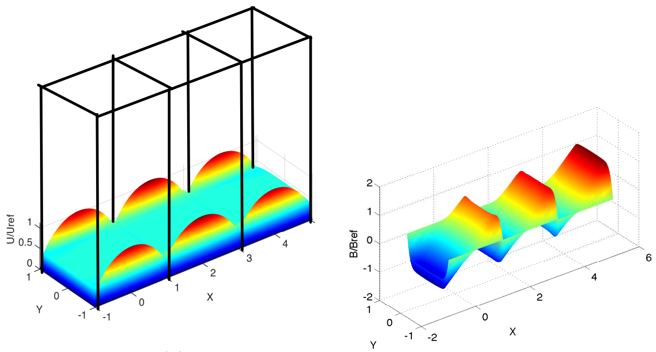
Surface heat transfer



Volumetric heat transfer

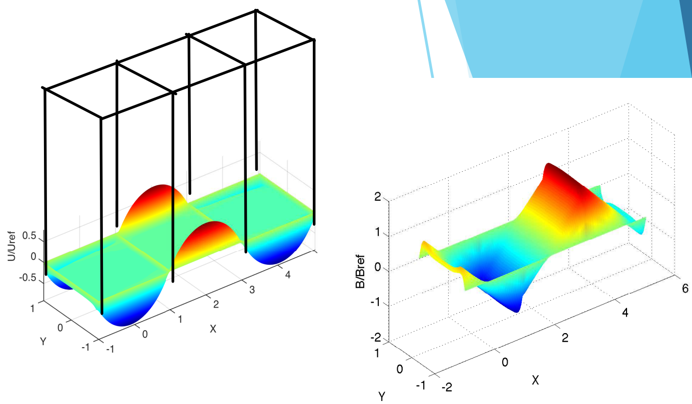
Magneto-hydrodynamic effects: coupling between ducts

- Parallel channels can couple through their magnetic fields
- Co-flow (same flow direction) effectively reduces wall friction
- Counter-flow (opposing directions) effectively increases wall friction
- Can even cause flow reversal

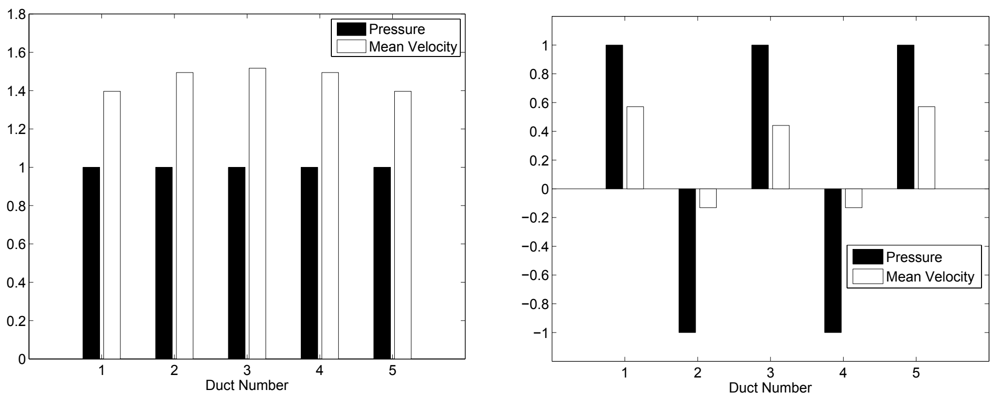


(a) (b)

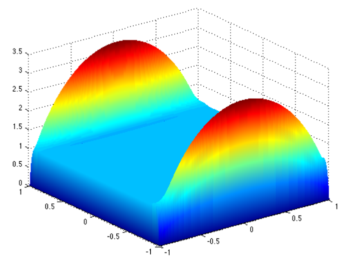
Co-flow



(a) Counter-flow (b)



(a) (b)



Flow profile in a single duct

Bluck, Michael J., and Michael J. Wolfendale. "An analytical solution to electromagnetically coupled duct flow in MHD." *Journal of Fluid Mechanics* 771 (2015): 595-623.

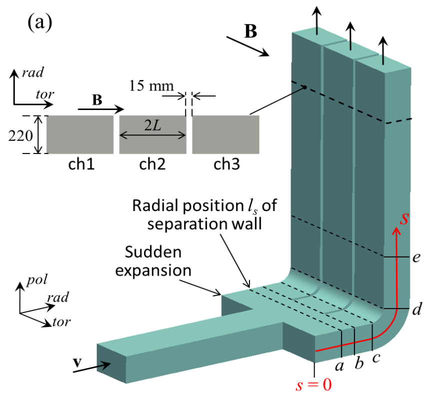
Computational Magneto-hydrodynamics

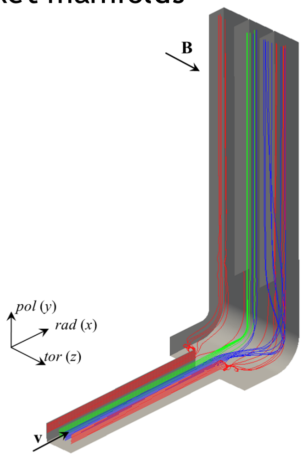
$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho}\nabla p + \frac{\nu}{\rho}\nabla^2 \mathbf{u} + \frac{1}{\rho}\mathbf{j} \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_f \sigma_f}\nabla^2 \mathbf{B} + (\mathbf{B} \cdot \nabla)\,\mathbf{u} - (\mathbf{u} \cdot \nabla)\,\mathbf{B}$$

- As in fission, complex geometry needs full 3D CFD
- Less well developed than conventional CFD
- MHD turbulence suppression makes conventional RANS models invalid
- Extremely thin wall shear layers result in many cells
- Improvements in MHD-CFD needed:
  - Improved geometry and field modelling (eg isogeometric methods)
  - Turbulence models

Flows in blanket manifolds





C Mistrangelo and L Buhler. "MHD flow in a prototypical manifold of DCLL blankets." (2014) *KIT Scientific Reports SR 7673.*

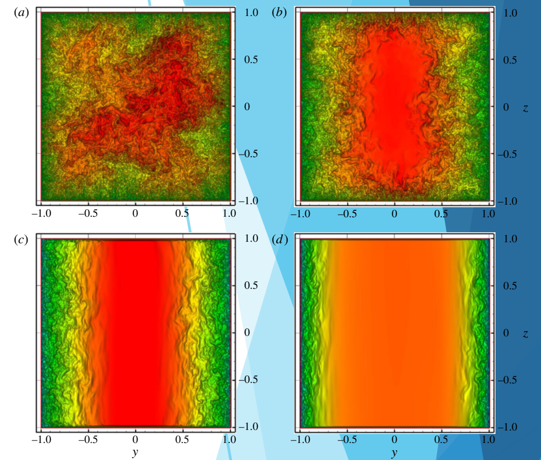
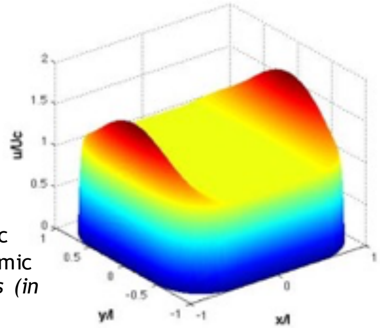


FIGURE 2. Instantaneous distributions of streamwise velocity at $x = L_x/2$. The contour levels are the same in all plots ranging from 0 (blue) to 1.25 (red). Note that the levels corresponding to blue are virtually invisible due to the very sharp velocity gradients at the walls: (a) $Ha = 0$; (b) $Ha = 100$; (c) $Ha = 200$; (d) $Ha = 300$.

D Krasnov, et al. "Numerical study of MHD duct flow at high Reynolds and Hartmann numbers." *Journal of Fluid Mechanics (2012) 704, pp 421-446.*

Isogeometric FEA to model MHD flow in curved wall ducts (Enhanced structural integrity)



Ji Soo Ahn, and Michael J Bluck. "Isogeometric analysis of fully developed magnetohydrodynamic duct flows." *Journal of Computational Physics (in press).*

Systems code – MHD CFD coupling

- As in fission, we need to bridge plant and component scales
- We take a similar approach
- In house systems code, embodying new MHD correlations
- openFoam based MHD CFD solver
- Communications using TCP/IP protocols
- Manifold modelled using CFD
- Duct array using systems code

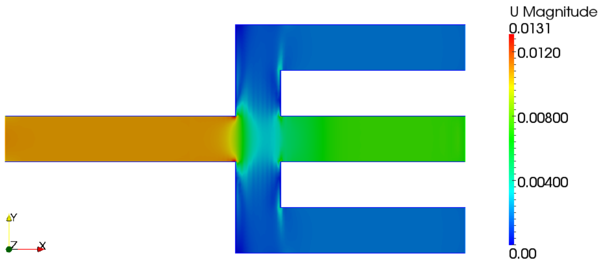


Figure 7.26: Triple outlet duct manifold velocity contour plot for case B = 1T, Ha = 108, t_w = 0.01. Manifold region insulating, outlet ducts conducting with no EM coupling.

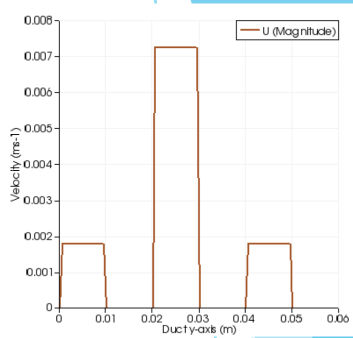


Figure 7.28: Manifold outlet 1 y-axis velocity profile at x = 0.095m for B = 1T, Ha = 108, t_w = 0.01, non EM coupling case.

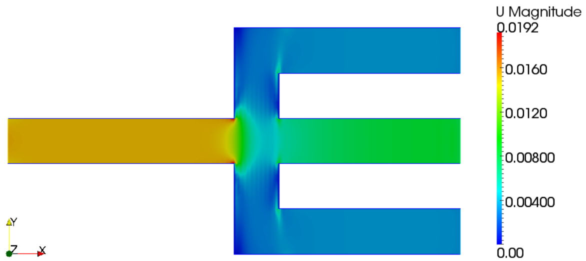


Figure 7.31: Triple outlet duct manifold velocity contour plot for case B = 1T, Ha = 108, t_w = 0.01. Manifold region insulating, outlet ducts conducting with EM coupling.

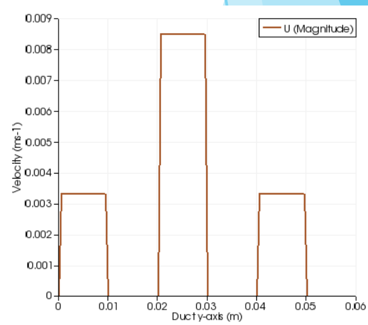


Figure 7.32: Manifold outlet velocity profile at x = 0.095m for B = 1T, Ha = 108, t_w = 0.01. EM coupling case.

Wolfendale, Michael J., and Michael J. Bluck. "A coupled systems code-CFD MHD solver for fusion blanket design." *Fusion Engineering and Design* (2015).

Conclusions

- Focus of fusion activity will shift toward technology, in which fusion blankets play a vital role
- The fundamental understanding, experimental facilities and analysis tools are much less well developed than in fission, but the benefits of a similar approach are clear
- Again, I have focused on issues central to thermal hydraulics, but these influence and are influenced by many related fields, eg.
  - Materials
  - Corrosion
  - Tritium generation & transport

Many thanks!