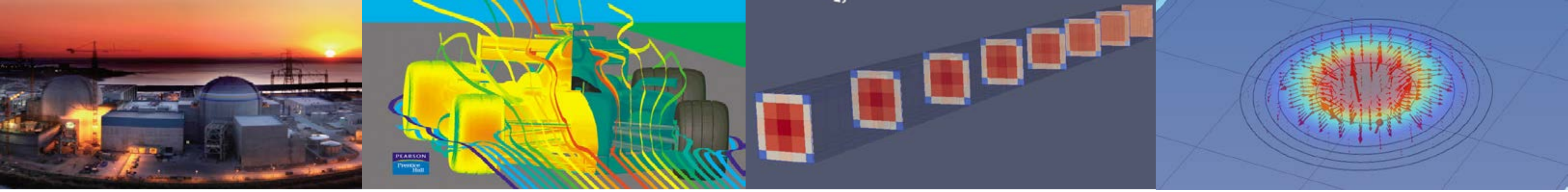

COMPUTATIONAL NUCLEAR THERMAL HYDRAULICS

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NuTHEL
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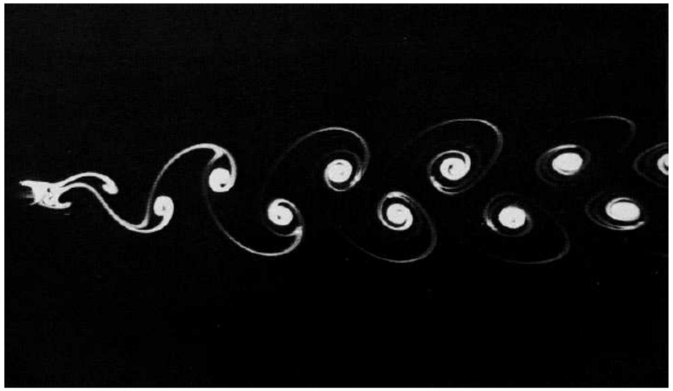
0. COURSE OVERVIEW

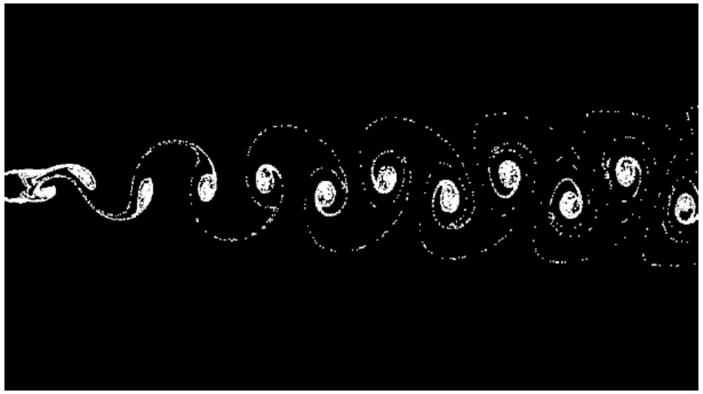
Background

- Computational Fluid Dynamics
  - A branch of computer-based science that provides predictions of fluid flows
  - Mathematical modeling (typically a system on non-linear, coupled PDEs)
  - Numerical methods (discretization and solution techniques)
  - Software tools

  - CFD enables scientists and engineers to perform ‘numerical experiments’ (i.e. computer simulations) in a ‘virtual flow laboratory’.



Real experiment



CFD simulation

Background

- Computational Fluid Dynamics
  - Experiments vs. simulations
    - CFD gives an insight into flow patterns that are difficult, expensive or impossible to study using traditional (experimental) techniques

Experiments	Simulations
Quantitative description of flow phenomena using measurements	Quantitative prediction of flow phenomena using CFD software
• for one quantity at a time • at a limited number of points and time instants • for a laboratory-scale model • for a limited range of problems and operating conditions	• for all desired quantities • with high resolution in space and time • for the actual flow domain • for virtually any problem and realistic operating conditions
Error sources: measurement errors, flow disturbances by the probes	Error sources: modeling, discretization, iteration, implementation

Background

Computational Fluid Dynamics

- As a rule, CFD does not replace the measurements completely but the amount of experimentation and the overall cost can be significantly reduced.

Experiments	Simulations
• expensive	• cheap(er)
• slow	• fast(er)
• sequential	• parallel
• single-purpose	• multiple-purpose
• Difficult to transport	• Portable, easy to use and modify

- The results of a CFD simulation are never 100% reliable because
  - the input data may involve too much guessing or imprecision
  - the mathematical model of the problem at hand may be inadequate
  - the accuracy of the results is limited by the available computing power

- It is not a magic tool !

Background

- Computational Fluid Dynamics
  - Classification of fluid flows

• Viscous	• Inviscid
• Compressible	• Incompressible
• Steady	• Unsteady
• Laminar	• Turbulent
• Single -phase	• Multiphase

  - The reliability of CFD simulations is greater
    - For laminar/slow flows than for turbulent/fast ones
    - For single-phase flows than for multi-phase flows
    - For steady than for unsteady flow
  - Nuclear thermal-hydraulics
    - Unsteady flow: fast transient
    - Highly turbulent flow
    - Mutliphase flow: various flow patterns

+ complexity of geometry
+ insufficient validation data
+ lack of universal governing equations

CFD in Nuclear Reactor Safety

CFD in NRS

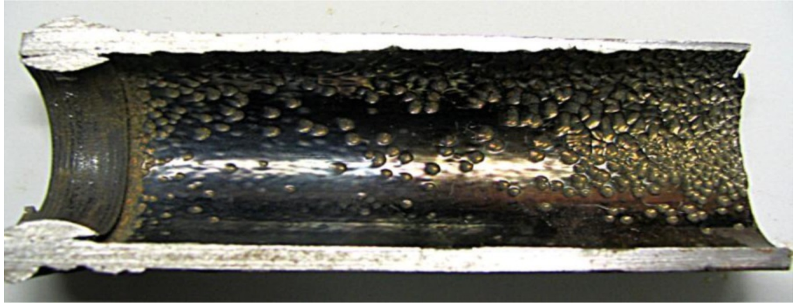
- Lead by OECD/NEA/CSNI
  - OECD: Organization for Economic Co-operation and Development
  - NEA: Nuclear Energy Agency
  - CSNI: Committee on the Safety of Nuclear Installations

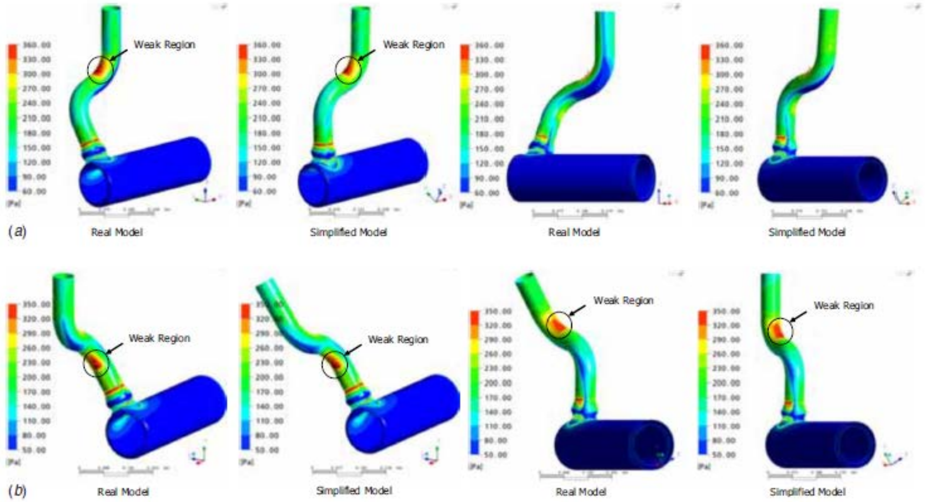
- Provided practical guideline for application of single phase CFD to NRS
  - To perform high quality CFD analysis
  - The applications of 1-ϕ CFD were wide spread in NRS community and in need of systematic guidelines for use.

- Phenomena
  - Containment wall condensation
  - Pipe wall erosion (Flow accelerated corrosion)
  - Thermal cycling (thermal fluctuation)
  - Hydrogen explosion
  - Fire analysis
  - Water hammer
  - Liquid metal system
  - Natural convection

CFD in Nuclear Reactor Safety

- CFD in NRS
  - FAC





18” elbow wall thickness decreased from 12.7 to 1.5 mm on feed-water pump inlet at Surry, 1986

Wall Thickness reduced from 10 to 1.5 mm on Feed-water piping at Mihama unit 3, 2004

Failure in a high pressure extraction line at Fort Calhoun in 1997

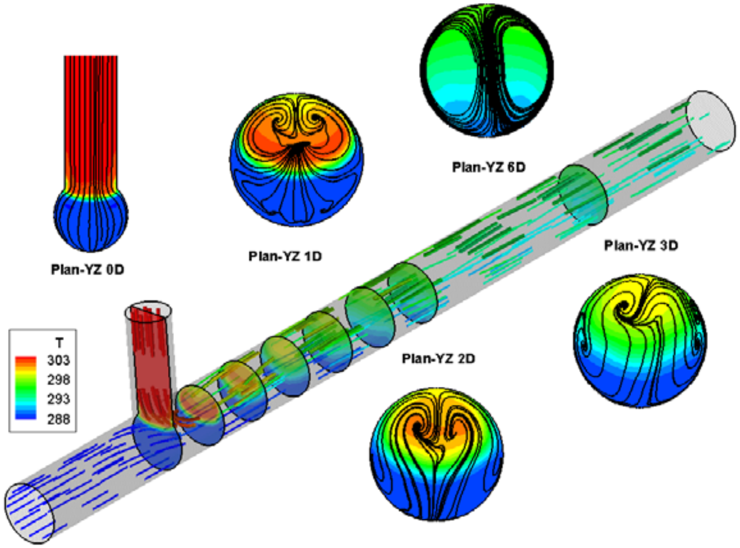
Failure downstream of the LCV in the reheater drain line at Millstone unit 2, 1991.

Failure of 14” heater drain extraction line to high pressure heater at Arkansas unit 2, 1986

Failure of the Feed-water Heater Point Beach Unit 1, 1999

CFD in Nuclear Reactor Safety

- CFD in NRS
  - Thermal cycling
    - Thermal stripping
    - High frequency thermal fluctuation on the inner surface of a component
    - Can cause the propagation of deep cracks
    - Civaux N4 class reactor
      - shut down in May 1998 following a leak of primary coolant from a pipe in the Residual Heat Removal (RHR) system



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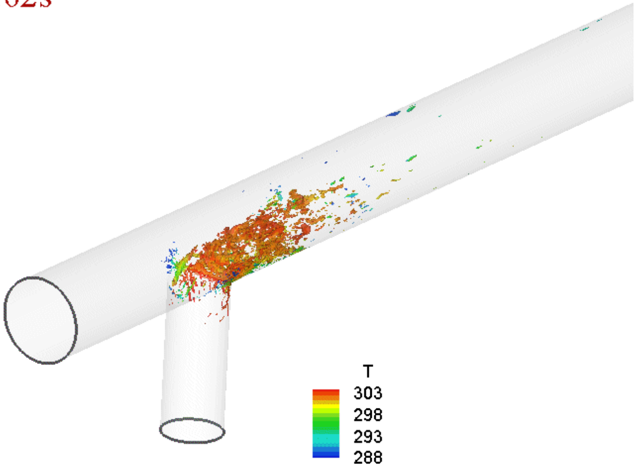
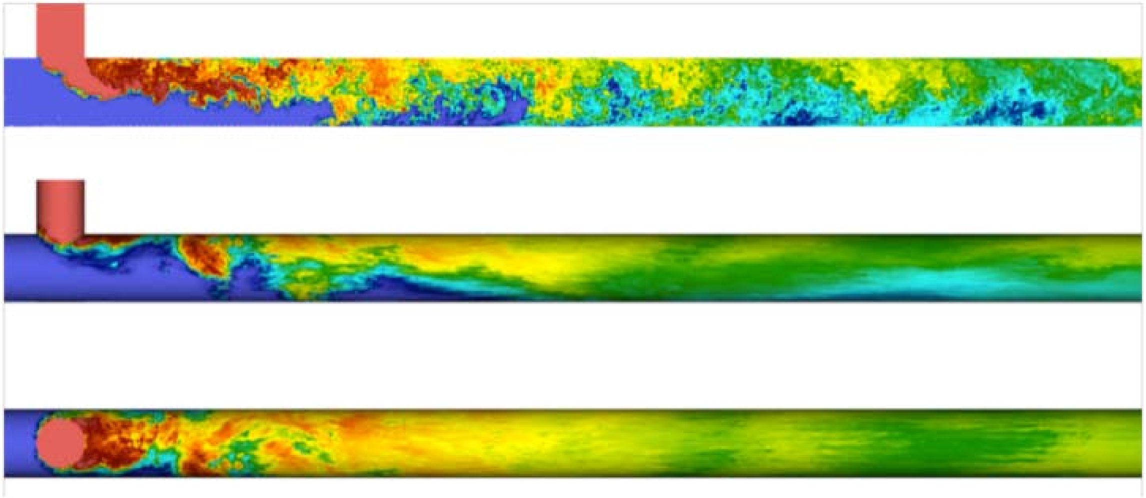
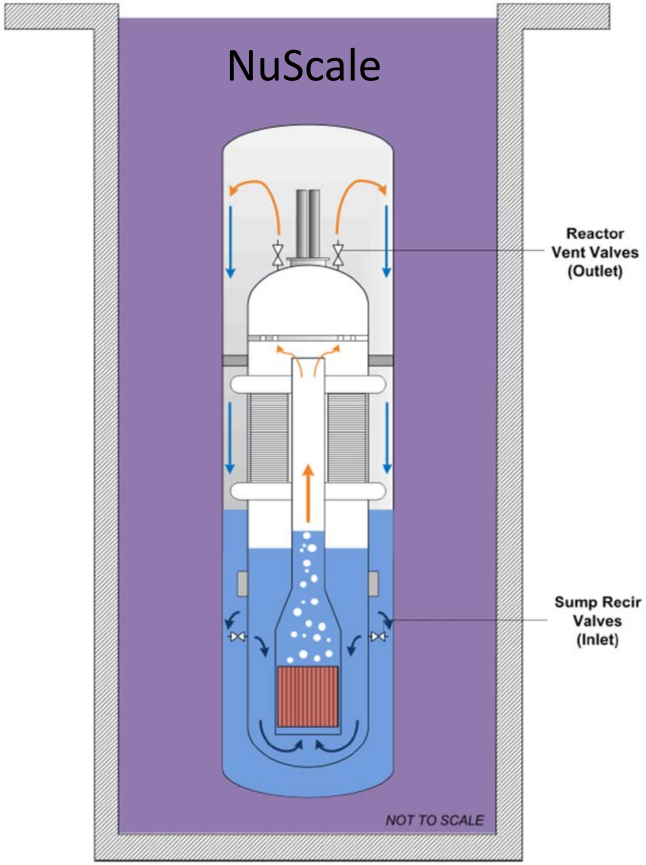




CFD in Nuclear Reactor Safety

- CFD in NRS
  - Natural convection
    - Passive mechanism of heat removal
    - Small modular reactors
    - Passive safety systems



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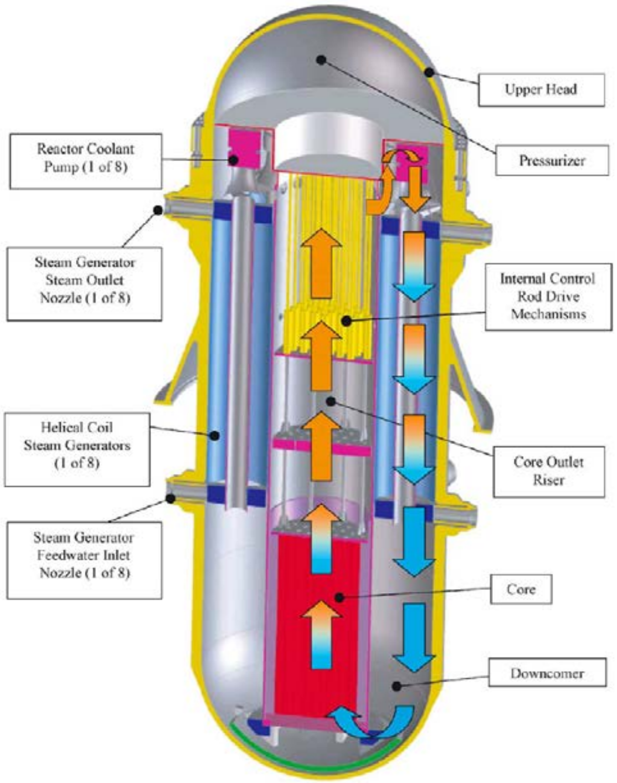

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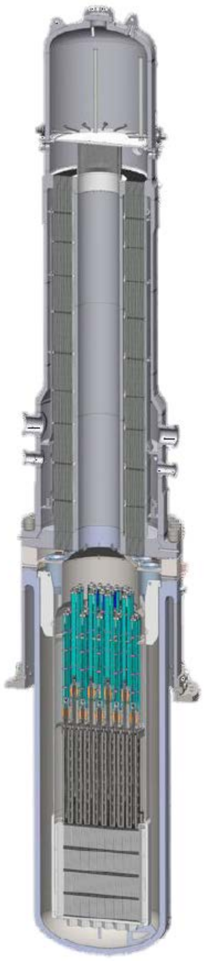
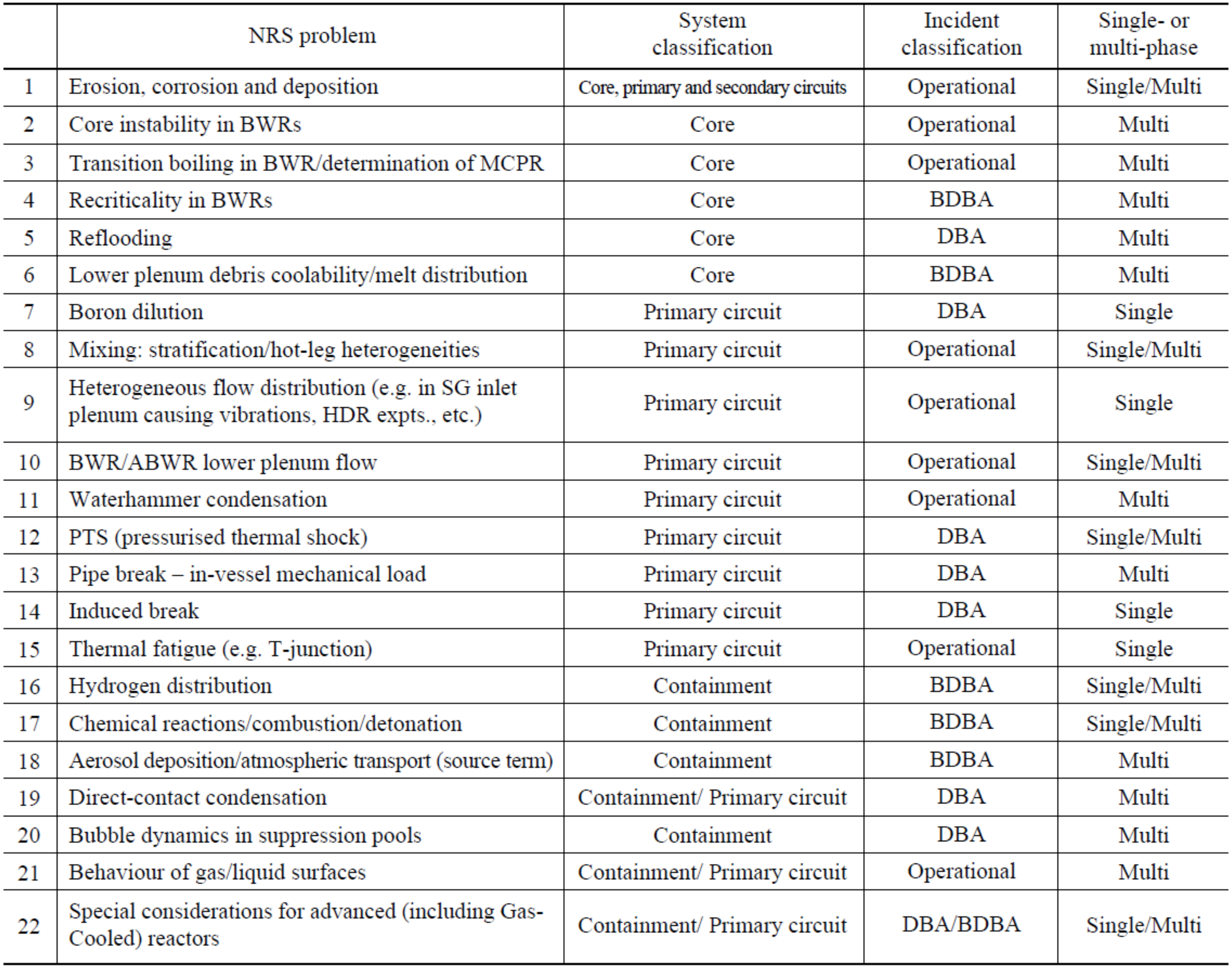


CFD in Nuclear Reactor Safety

- CFD in NRS



	NRS problem	System classification	Incident classification	Single- or multi-phase
1	Erosion, corrosion and deposition	Core, primary and secondary circuits	Operational	Single/Multi
2	Core instability in BWRs	Core	Operational	Multi
3	Transition boiling in BWR/determination of MCPR	Core	Operational	Multi
4	Recriticality in BWRs	Core	BDBA	Multi
5	Reflooding	Core	DBA	Multi
6	Lower plenum debris coolability/melt distribution	Core	BDBA	Multi
7	Boron dilution	Primary circuit	DBA	Single
8	Mixing: stratification/hot-leg heterogeneities	Primary circuit	Operational	Single/Multi
9	Heterogeneous flow distribution (e.g. in SG inlet plenum causing vibrations, HDR expts., etc.)	Primary circuit	Operational	Single
10	BWR/ABWR lower plenum flow	Primary circuit	Operational	Single/Multi
11	Waterhammer condensation	Primary circuit	Operational	Multi
12	PTS (pressurised thermal shock)	Primary circuit	DBA	Single/Multi
13	Pipe break – in-vessel mechanical load	Primary circuit	DBA	Multi
14	Induced break	Primary circuit	DBA	Single
15	Thermal fatigue (e.g. T-junction)	Primary circuit	Operational	Single
16	Hydrogen distribution	Containment	BDBA	Single/Multi
17	Chemical reactions/combustion/detonation	Containment	BDBA	Single/Multi
18	Aerosol deposition/atmospheric transport (source term)	Containment	BDBA	Multi
19	Direct-contact condensation	Containment/ Primary circuit	DBA	Multi
20	Bubble dynamics in suppression pools	Containment	DBA	Multi
21	Behaviour of gas/liquid surfaces	Containment/ Primary circuit	Operational	Multi
22	Special considerations for advanced (including Gas-Cooled) reactors	Containment/ Primary circuit	DBA/BDBA	Single/Multi

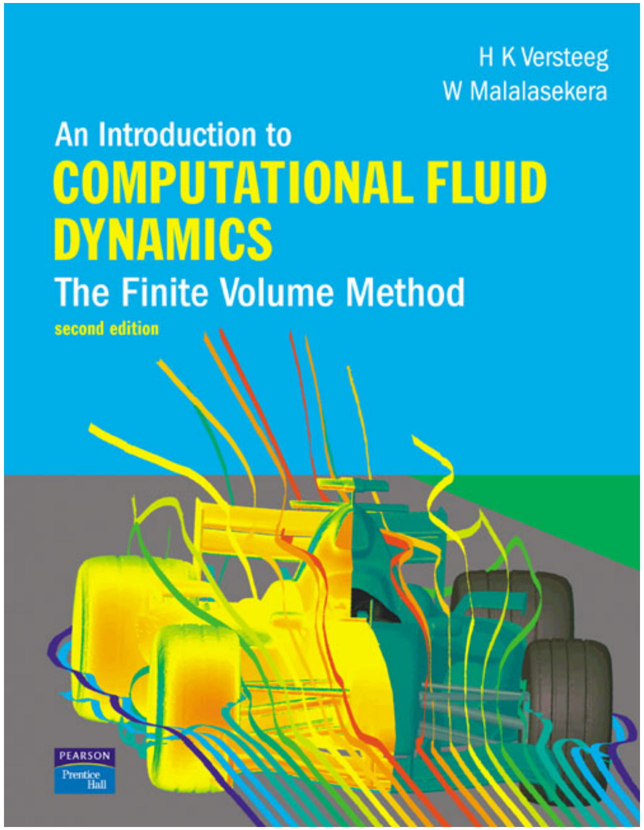
Course Description

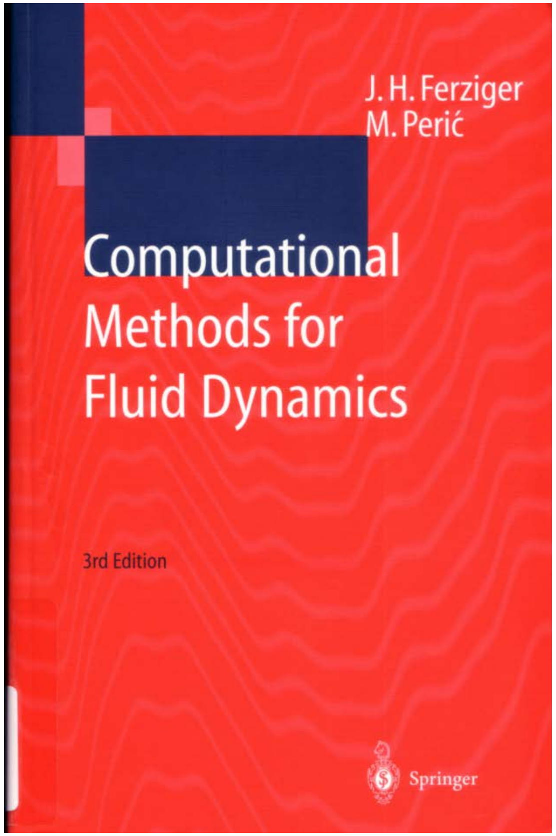
- Aim of Course
  - First part
    - To provide insight into the philosophy and power of numerical fluid simulations
    - To give a basic understanding to the discretization of equations of mass and momentum (Navier-Stokes' Eqs.)
    - Knowledge of different solution methods
    - To write CFD codes for some benchmark two-dimensional flow problems on Cartesian grids

  - Second part
    - Governing equations of two-phase flow
    - Numerical method for two-fluid model
    - Constitutive relations
    - Practice with KAERI's inhouse code CUPID

Course Description

- Literature (for the first part)
  - "An Introduction to Computational Fluid Dynamics" H. K. Versteeg and W. Malalasekera, 2nd Edition, Pearson, 2007.
  - *"Computational Methods for Fluid Dynamics,"* 3rd Edition, J.H. Ferziger and M. Peric, Springer-Verlag, 2002, ISBN 3-540-42074-6.





Course Description

- Course outline (for the first part)

Week	Contents	Specification
1	Conservation laws of fluid motion and boundary conditions	
2-3	The finite volume method for diffusion problems	HW1
3-4	The finite volume method for convection-diffusion problems	HW2
5-6	Solution algorithms for pressure-velocity coupling in steady flows	HW3
7	The finite volume method for unsteady flows	HW4
8	Turbulence and its modeling	

Course Description

- Course outline (for the second part)

Week	Contents	Specification
9	Two-phase flow models/two-fluid model	
10-11	CUPID practice	HW5
12	Numerical method for two-phase flow	
13	Closure relations for two-phase flow	
14	Project presentation	
15	Project presentation	HW6

Course Description

- Grading policy
  - HW for the first part: 60 %
  - HW for the second part: 40 %