CFD Applications in Nuclear Reactor Safety

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Overview

Motivation

Networks

Application areas

• Validation
• Industrial applications

Best practices

• OECD Best Practice Guidelines

Summary & outlook
CFD - Motivation

Simulation tasks

- Quantification of safety margins
- Assessment of performance increases
- New strategies for core loading & management

CFD applications

- Multi-dimensional phenomena
- Complement to system codes

CFD development needs

- Physics – Turbulence, heat transfer, combustion, multiphase flows, ...
- Numerics - Speed
CFD Networks in Nuclear Reactor Safety

**German CFD Network**
- [http://cfd.grs.de](http://cfd.grs.de)

**International OECD Task Group**
- [www.oecd-nea.org/nsd/csni/cfd](http://www.oecd-nea.org/nsd/csni/cfd)

**Objectives:**
- Best practice guidelines
- Assessment of CFD codes for NRS
- CFD4NRS workshops & benchmarks
Nuclear Reactor CFD

Primary system & core
Secondary system
Containment & sump
Emission
Deposition
Storage, ...
Primary System & Core

Quantification of safety margins

Life extension
- Material fatigue
- Pressurised thermal shocks

Re-criticality
- Boron dilution & mixing
- Ballooning

Fuel behaviour
- Neutron kinetics & CFD coupling
Primary Circuit & Core – Model Requirements

**Turbulence**
- Unsteady-state mixing
- Buoyancy & stratification

**Energy transfer**
- Convection & conduction $\rightarrow$ conjugate heat transfer

**Multi-phase flows**
- Bubbles $\rightarrow$ free surfaces
- Condensation & boiling

**Multi-physics & multi-scale**
- Fluid-thermal & fluid-structure
- Neutron kinetics & CFD
- System & field $\rightarrow$ ATHLET-2-CFD
Containment & Sump

Discharges of primary or secondary circuits

Hydrogen distribution in containments

Recombiners

Condensation

Detonation & deflagration

Containment integrity
Containment & Sump – Model Requirements

Turbulence
- Unsteady-state mixing
- Buoyancy & stratification

Energy transfer
- Convection & conduction → conjugate heat transfer
- Radiation

Multi-phase flows
- Free-surface flows
- Condensation

Chemical reactions
- Combustion → deflagration → detonation
- Recombiners

Multi-physics
- Fluid-structure
Nuclear Reactor Safety & CFD Quality

Objective
- Use of CFD results for quantitative safety-critical analyses

Requirements
- Accuracy
- Reliability
- Robustness
- Fault tolerance

Quality
- Quantification of numerical errors
- Estimation of model errors
- Uncertainty quantification
- Knowledge management
- Competence management → best practices
Best Practice Guidelines


Requirement specification
- Cost & effort
- Accuracy
- Validation or “production”

Best Practice Guidelines
- Procedures & processes
- Checklists

Knowledge management
- Education
- Awareness
Best Practice Guidelines - Elements

Model selection
Geometry model - domain
Grid – model requirements & quality

Simulation – HPC, ...
Material properties - uncertainties
Initial & boundary conditions – uncertainties

Error quantification – iteration, discretisation, model, ...
Uncertainty analysis – sensitivities & robustness
Documentation & knowledge management
Best Practice Guidelines - Elements

- Model selection
- Geometry model
- Grid
- Initial & boundary conditions
- Material properties
- Simulation
- Error quantification
- Uncertainty analysis
- Documentation
Best Practice Guidelines: Grid Generation

Scalable grids

Grid angles $> 20^\circ$ and $< 160^\circ$ (accuracy, convergence)

Expansion ratios $< 1.5 \ldots 2$

Aspect ratios – $f$(solution algorithm)

Turbulence model requirements

Grid lines aligned with streamlines $\rightarrow$ walls

Capture physics based on experience (shear layers, free surfaces, ...)
Best Practice – Turbulence Model Recommendations

- Proven technology
- Consistency
- Diversity → consolidation

URANS
- SST model
- Automatic wall functions

Scale-resolving hybrid
- SAS
- DDES
- ...
- ZLES

Scale-resolving
- LES
- WMLES
Best Practice – Example

Large Scale Test Facility (LSTF)
- Height = 4-loop 1100 MW Westinghouse PWR
- Volume scale: 1:48
- Scaled nominal power: 2%

OECD/NEA ROSA V
- Buoyancy-driven stratified flow
- ECC injection in cold leg
- Natural circulation condition
- Temperature stratification

Source: T. Yonomoto 2005, JAERI
BPG – Model, Geometry, Initial & Boundary Conditions

Model
- URANS – SST & RSM

Geometry
- Half model for BPG
- Full model for production

Initial condition
- Steady-state natural circulation

Boundary conditions @ cold legs and ECC nozzle
- Inlet mass flow rates
- Inlet temperature
- Pressure @ downcomer bottom
BPG: Numerical Grids

- **Coarse mesh**
  - 1 million elements

- **Medium mesh**
  - 5 million elements

- **Fine mesh**
  - 8 million elements
BPG: Iteration Error

Temperature [K]

Residual target of the convergence criterion

TE1177
TE1180
TE1183
TE1184
BPG: Discretisation Error

Influence of grid size & time step

Compromise between accuracy & computational effort
BPG: Model Error

Turbulence model
- SST
- RSM

Calculation time
- RSM = 1.4 × SST

Centerline, time = 50 s
BPG – Validation: Comparison to Data

CLA - TE3

Downcomer - TE4

TE1205

TE1232
Error Estimation $\rightarrow$ Large Problem Sizes

**Reactor system**
- Grid: 20 million elements
- 1000 s real time

**Solution**
- Document uncertainties

**Research**
- Error-adaptive schemes
- HPC
- Discretisation schemes
- Solution algorithms
- Coupling CFD & system codes
Summary and Outlook

CFD in NRS

Higher accuracy & detail requirements  Increased use

Application areas

Primary system  ...  containment  ...  storage

Simulation requirements

Accuracy, efficiency, robustness  Quality  Best practice guidelines

Promising technologies

<table>
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<th>Hybrid scale-resolving turbulence models</th>
<th>“Baseline” multi-phase flow models</th>
<th>HPC</th>
<th>System-2-field coupling</th>
<th>Multi-physics</th>
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Higher accuracy & detail requirements lead to increased use. Application areas include primary system, containment, and storage. Simulation requirements focus on accuracy, efficiency, and robustness, leading to quality improvements and best practice guidelines. Promising technologies include hybrid scale-resolving turbulence models, "baseline" multi-phase flow models, HPC, system-2-field coupling, and multi-physics.