Creation of Best Practice Guidelines for the Use of CFD in Nuclear Reactor Safety Applications

John Mahaffy

Penn State University

Applied Research Laboratory

Background

In May 2002, an “Exploratory Meeting of Experts to Define an Action Plan on the Application of Computational Fluid Dynamics (CFD) Codes to Nuclear Reactor Safety Problems” was held at Aix-en-Provence, France. One of three recommended actions was the formation of this writing group to report on the need for guidelines for use of CFD in single phase Nuclear Reactor Safety (NRS) applications.

An initial needs study was performed between March 2003 and September 2004 resulting in a summary of existing guidelines, and a recommendation to the write NRS specific guidelines. See:

> Mahaffy, J.H., P. Dietrich, F. Ducros, M. Henrikson, P. Fantoni, T. Morii, P. Muhlbauer, M. Scheuerer, B.L. Smith, and T. Watanabe, “Guidelines for the use of CFD in Nuclear Reactor Safety Applications,” OECD Nuclear Energy Agency Report NEA/SEN/SIN/AMA(2005)2 (January 2005)

Writing Group 1
Best Practice Guidelines

- CAPS Objectives:

  "This activity will produce a set of best practice guidelines for application of single phase Computational Fluid Dynamics (CFD to Nuclear Reactor Safety (NRS) applications."

- Writing Activities began in January 2005, first working draft was produced in August 2005, and a draft was provided for GAMA review and comments in August 2006

- Lead Organization: U.S. Nuclear Regulatory Commission

- Participants:

  Czech Republic (NRI), France (CEA, IRSN), Germany (GRS, FZR), Italy (U. of Pisa), Japan (JNES, JAEA), Korea (KAERI), Netherlands (NRG), Sweden (Vattenfall), Switzerland (PSI), US (NRC)

The Resulting CSNI Report

Mahaffy, J.H., B. Chung, F. Dubois, F. Ducros, E. Graffard, M. Heitsch, M. Henriksson, E. Komen, F. Moretti, T. Morii, P. Mühlbauer, U. Rohde, M. Scheuerer, B. L. Smith, C. Song, T. Watanabe, G. Zigh, “Best Practice Guidelines for the use of CFD in Nuclear Reactor Safety Applications,” OECD Nuclear Energy Agency, CSNI Report NEA/CSNI/R(2007)5 (May 2007)

Specific Document Objectives

- Outline the key steps and considerations in the production of a high quality CFD simulation. However, we assume existence of sufficient theoretical background in fluid dynamics, and only introduce discussion in this area where it directly contributes to the choice of simulation code or user option for a specific simulation code.
- Provide references to existing CFD simulations for NRS problems.
- Provide an internally complete set of guidelines for a range of single phase applications of CFD to NRS problems.
- Provide direct guidance on the key considerations in known single phase applications, and general directions for resolving remaining details.
- Serve as a template for future application specific BPG Documents (e.g. PTS, induced break) that will provide much more detailed information and examples.

Document Contents

Problem Definition

- **Isolation of the Problem**

  Selection of the region of interest for CFD, and use of a systems code for CFD boundary conditions

- **PIRT**

  This provides an outline of the process developed by the U.S. NRC to identify and rank significant phenomena in a system transient scenario. The process also reviews appropriateness of proposed simulation tools, and suggests an experimental basis for validation of results.

- **Special Phenomena**

  This section discusses special considerations for attacking problems in: containment wall condensation; pipe wall erosion; thermal cycling; hydrogen explosion; fire analysis; water hammer; liquid metal systems; and natural convection.

Selection of an Appropriate Simulation Tool

This section reviews capabilities of the full range of available simulation tools.

- Classic Thermal-Hydraulic System Codes
- Component Codes
- CFD Codes
- Potential Complementary Approaches (e.g. coupling CFD to a TH systems code)

User Selection of Physical Models

- Guidelines for turbulence modeling in NRS applications
    - o Selection between RANS, U-RANS, LES, DES, DNS
- Buoyancy Model
- Heat Transfer
- Free Surface Modeling
- Fluid-Structure Interaction

User Control of the Numerical Model

- Transient or Steady Model
  - o Note that LES, DES, and DNS are fundamentally transient models.
- Grid Requirements
  - o Choice of geometry and grid
  - o Quality of grid
- Discretization Schemes
- Convergence Control
  - o Convergence to solution of the model PDEs
  - o Convergence to solution of non-linear discrete equations
- Free Surface Considerations
  - o Use of boundary conditions, VOF, and Level Sets

Assessment Strategy

- A brief chapter is provided outlining a general strategy for assessment of the CFD simulation
- Application of Verification and Validation is introduced here and discussed in more detail in the following two chapters
- Demonstration of Capabilities
- Interpretation of Results
    - o Qualitative comparison of results
    - o Quantitative comparison of target variables
    - o Inclusion of simulation and experimental uncertainties.

Verification of the Calculation and Numerical Model

- Error Hierarchy and choice of target variables
- Round-off Errors
- Iteration Errors
- Spatial Discretization Errors
  - o Use of Richardson Extrapolation analysis
- Time Discretization Errors
- Software and User Errors, Application of QA principles

Validation of Results

- Validation Methodology
    - o Tiered Approach
    - o Validation Experiments
- Target Variables and Metrics
- Treatment of Uncertainties
    - o Experimental Uncertainties
    - o Uncertainty in the Simulation Results

Special Consideration of Specific NRS Cases

This section discusses some specific CFD analyses of important safety problems. The examples provide an overview of the work and application specific considerations but are not intended to provide detailed guidelines for the applications.

- Boron Dilution – ROCOM facility
- Pressurized Thermal Shock - UPTF
- Spent Fuel Dry Storage Cask – VSC-17 Cask Experiments
- Hydrogen Mitigation in Containment – PAKS VVER-440 Containment

Checklist for a Calculation

Because of the length of the document, we have provided a very brief Annex listing key considerations when performing CFD analysis. Where appropriate, references are given to sections in the body of the document. Areas covered are:

- Initial Preparation
- Geometry Generation
- Selection of Physical Models
- Grid Generation
- Numerical Methods
- Verification
- Validation

Future BPG Revisions and Extensions

- We have received useful comments on the document since its publication. A process is now being developed to convert this to a living document, maintained as a Wiki on the NEA web site.
- Single phase CFD is mature to the extent that it now runs relatively robustly, and contains a good range of options for modeling turbulence and flow through complex geometries. However, CFD applications still push the limits of computational resources. As computer speed and memory capacity continues to expand, we can expect adaptation of more detailed modeling approaches and corresponding shifts in general guidelines.
- As indicated in our original survey of the need for Best Practice Guidelines (NEA/SEN/SIN/AMA(2005)2), the general BPG document needs to be supplemented by application specific BPGs (e.g. BPG for analysis of PTS). Generation of these specific documents could be done in association with International Standard Problems.
- Guidelines (both general and application specific) will also be needed for two-phase CFD.