ON APPLICATION OF CFD CODES TO PROBLEMS OF NUCLEAR REACTOR SAFETY

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ABSTRACT

The "Exploratory Meeting of Experts to Define an Action Plan on the Application of Computational Fluid Dynamics (CFD) Codes to Nuclear Reactor Safety Problems" held in May 2002 at Aix-en-Provence, France, recommended formation of writing groups to report the need of guidelines for use and assessment of CFD in single-phase nuclear reactor safety problems, and on recommended extensions to CFD codes to meet the needs of two-phase problems in nuclear reactor safety. This recommendation was supported also by Working Group on the Analysis and Management of Accidents and led to formation of three Writing Groups. The first Writing Group prepared a summary of existing best practice guidelines for single phase CFD analysis and made a recommendation on the need for nuclear reactor safety specific guidelines. The second Writing Group selected those nuclear reactor safety applications for which understanding requires or is significantly enhanced by single-phase CFD analysis, and proposed a methodology for establishing assessment matrices relevant to nuclear reactor safety applications. The third writing group performed a classification of nuclear reactor safety problems where extension of CFD to two-phase flow may bring real benefit, a classification of different modelling approaches, and specification and analysis of needs in terms of physical and numerical assessments. This presentation provides a review of these activities with the most important conclusions and recommendations.

1. INTRODUCTION

Recommendations of the "Exploratory Meeting of Experts to Define an Action Plant on the Application of Computational Fluid Dynamics (CFD) Codes to Nuclear Reactor Safety Problems" held in May 2002 at Aix-en-Provence, France, led to formation of three Writing Groups (WG's) under co-ordination of OECD/NEA/GAMA with the following main tasks:

- Based on analysis of existing best practice guidelines (BPG's) for single-phase CFD analyses, and of flows in nuclear reactor safety (NRS) applications for which understanding requires or is significantly enhanced by single-phase CFD analysis, to make a recommendation on the need for NRS specific guidelines (WG 1).
- After critical review of those NRS problems where the use of single-phase CFD is needed or is beneficial and of corresponding existing assessment basis for CFD application to these NRS issues, to propose a methodology for establishing assessment matrices relevant to NRS needs (WG 2).
- After critical review of those NRS problems where the use of two-phase CFD is needed or is beneficial and of corresponding existing assessment basis for CFD application to these NRS issues, to give guidance for future development and assessment of two-phase CFD tools to be used in NRS problems (WG 3).

The first task is described in detail in Chapter 2 of this document, whereas Chapter 3 is devoted to the last two tasks. Main conclusions are presented and the relevant documents produced by the WG's are referenced.

2. BEST PRACTICE GUIDELINES FOR NRS APPLICATIONS OF CFD

Writing Group 1 in Ref. 1 recommended preparation of two types of documents to help CFD code users in preparation of input models and running and analysing of a CFD calculation: a general, but internally complete document, and several application specific documents. The WG 1 members should prepare the general document before June 2006. The application specific documents will be produced with help of organizations with direct experience in the specific analysis. The process of creating and exercising international standard problems would be a particularly good venue for creation of these specific BPGs.

The suggested contents of the general BPG as described in Section 5.1 of ref. 1 includes chapters on problem definition, selection of an appropriate simulation tool, user selection of physical models, user control of the numerical model, verification of calculation, validation of calculation, documentation, and special considerations for specific NRS cases. In problem definition, the role of the Phenomena Identification and Ranking Table (PIRT) is discussed. This approach should be used not only in preparation of calculation, but also in planning of validation experiments. The selected simulation tool (thermal-hydraulic system code, component code, or CFD code) must be used in verification ("solving the equations right"; comparison with known analytical solutions, or with solutions performed by a high-accuracy code) and validation ("solving the right equations"; comparison with suitable high-quality experiments) calculations for the intended application. Verification and validation calculations supplemented with demonstration calculations (calculations with no or very weak experimental support) and any suitable experimental observations then form a basis for assessment of the code (statement of appropriateness of the code with given selection of tools – physical models and numerical methods – to solve given problem). The chapters on selection of physical models and numerical methods will contain only general guidance in this document; more specific information should be given in the application specific documents.

The cases requiring specific guidelines known so far include hydrogen mixing in the containment, Western PWR cold leg connection to the downcomer (PTS, boron dilution transient, standard operating conditions), Western PWR lower and upper plena, VVER downcomer and lower plenum, BWR-ABWR lower plenum, Western PWR hot leg and steam generator inlet plenum (induced break), in-containment water storage tanks, and APWR accumulator. Each document needs to be tightly coupled to a project in which a well-designed CFD analysis is being performed (creation and execution of appropriate international standard test problems and similar benchmark activities are good examples).

The OECD/NEA should provide guidance for creation of these documents and an organized repository for the final products. The general BPGs will exist as a Web based HTML document maintained by the OECD/NEA, with cross-links to all application specific documents (and vice versa). Such Web site has been already established for internal needs of the Writing Group members (ID and password are required since not all documents contained are public at present).

3. ASSESSMENT OF CFD CODES FOR NRS PROBLEMS

The Writing Groups 2 and 3 reviewed critically those NRS problems, where the use of CFD is needed or where its use is expected to result in major benefits. Also the existing assessment basis for CFD application to NRS issues was reviewed and a methodology for establishing assessment matrices relevant to NRS needs was proposed. The gaps in the technology base and the need for further development effort were identified.

Ref. 2 and Ref. 3 contain lists of selected NRS issues with reasons for their selection. A shortened version of the lists is shown below. Issues possibly relevant to VVER reactors are treated in more detail.

The Writing Group 2 focused its attention to single-phase issues, but some multi-phase issues are also included in the list for completeness:

- **Erosion, corrosion and deposition.** An operational, single- or multi-phase issue, related to reactor core, and primary and secondary circuits. Local fluid velocities, temperatures, quality, pH level and oxygen content should be calculated in order to determine the rate of the erosion.
- **Core instability in BWRs**
- **Transition boiling in BWR.**
- **Reflooding.** A DBA, mainly two-phase issue, related to reactor core. The most significant flow phenomena affecting peak-clad temperature and taking place during reflooding are heterogeneous bottom-up and top-down quenching, post-CHF heat transfer, droplet break-up at spacer grids, complex radial mixing of the flow in the core, entrainment and de-entrainment of drops in the upper plenum, water droplets entrainment up to SGs, and steam binding effect. CFD codes should enable more detailed, more general description of these phenomena.

- **Lower plenum debris coolability/melt distribution.** A BDBA, multi-phase issue, related to the reactor core. CFD can be used to improve the accuracy of predictions in non-uniform beds (water penetration rates, relaminarization due to different grain sizes).
- **Boron dilution.** A DBA, single-phase issue, related to the primary circuit. Transportation of the boron-deficient water slug to the core in complex geometry (piping, down comer and lower plenum) with strong mixing was subject of several tests and numerical simulations (ISP-43, ROCOM tests and numerical simulations within the FLOMIX-R project, tests on the Gidropress facility modelling VVER-1000 reactor).
- **Mixing: stratification/hot-leg heterogeneities.** An operational, single- and multi-phase issue, related to primary circuit. Fluid mixing is in fact the most common fluid dynamic phenomenon, present in many other issues of this list (e.g., boron dilution, pressurized thermal shock, etc.).
- **Heterogeneous flow distribution.** An operational, single-phase issue, related to the primary circuit. Here, heterogeneous flow inside the pipes with bends can cause tube vibrations due to fluid-structure interaction (FSI) and even tube rupture. Application of CFD codes could lead to better prediction of quantities entering present vibration models used in system codes.
- **BWR/ABWR lower plenum flow.**
- **Waterhammer condensation.** An operational, multi-phase issue, related to the primary circuit. Strong pressure waves could be caused by fast closing or even opening of valves. When volume effects are involved, three-dimensional codes are required. Moreover, the waterhammer phenomenon can develop along with stratification (thermal or phase induced), radial pressure distribution, and three-dimensional turbulence effects. CFD may lead to more accurate predictions of these effects.
- **Pressurized thermal shock.** A DBA, single- and multi-phase issue, related to the primary circuit. Complex geometry and flow patterns (stratified flows, jets, cold plumes developing in the down comer) require detailed simulation with CFD codes taking into account wall-to-fluid heat transfer (conjugated heat transfer) and, in the two-phase case, direct-contact condensation. An assessment of capability of CFD codes to resolve the PTS transients was made e.g. within the ECORA and FLOMIX-R European projects, and this issue is treated also in the NURESIM project.
- **Pipe break.** A DBA, multi-phase issue, related to the primary circuit. Accurate, three-dimensional transient pressure field predictions are needed in order to estimate dynamic loadings on the internals after a pipe break.
- **Induced break.** A DBA, single-phase issue, related to the primary circuit. During certain accidents, the core is uncovered and heat is carried away by steam to structures in the reactor coolant system including the upper vessel, hot leg, and SG tubes. CFD simulation can resolve flow paths and flow-split ratios, and determine the three-dimensional thermal loads.
- **Thermal fatigue.** An operational, single-phase issue, related to the primary circuit. Either due to a defective valve, or in a T-pipe or down comer, there could be an unstable mixing of fluid with different temperatures causing thermal stripping. Such instability can be caused also by turbulence, and thermal stratification can be present. CFD simulations are able to predict thermal loading of metallic structures.
- **Hydrogen distribution.** A BDBA, single- or multi-phase issue, related to containment. Large-volume, multi-compartment containment geometry and very complex physics pose great demands on computational grids if numerical diffusion is to be avoided. Also temporal discretization is an important issue since several hours of transients must be simulated.

- **Chemical reactions/combustion/detonation.** A BDBA, single- or multi-phase issue, related to containment. For PWR containments that are not nitrogen inerted, but which have some mitigation systems (recombiners, for example), local hydrogen concentrations can exceed the flammability limits, at least during some stages of the accident scenarios. Deflagration, accelerated flames or even detonations are to be envisaged for some accident scenarios. Deflagrations are very complex phenomena, involving chemistry and turbulence. No adequate models exist to accurately describe deflagrations at large-scale and in complex geometries. CFD combined with flame-speed-based deflagration models can provide significant insight into the dynamic loading on the structures.
- **Aerosol distribution/atmospheric transport.** A BDBA, multi-phase issue, related to containment. The atmospheric dispersion of released nuclear materials in complex situations, such as the case of buildings in close proximity, is a difficult problem, but important to people living and working in such areas. CFD provides a method to build and run models that can simulate atmospheric dispersion in geometrically complex situations. Numerical modelling of building effects on the wind and dispersion poses several computational challenges. Firstly, computation of the flows around buildings requires knowledge of the characteristics of atmospheric boundary layers. In addition, knowledge of the mean wind speed and degree of atmospheric turbulence are also needed to accurately represent atmospheric winds, and the effects of the site, on dispersion. Secondly, topography of the configuration to be modelled is usually complex, especially in a nuclear power plant, where closely spaced groups of buildings are commonplace, with different individual topologies, heights and orientations. Consequently, great challenges are encountered when discretising the computational domain. Thirdly, the flows are highly complex, having all the elements that modern fluid dynamics has not yet successfully resolved. The major challenge lies in turbulence modelling. The difficulty is associated with the fact that the flows are highly three-dimensional, being accompanied, almost without exception, by strong streamline curvature, separation, and vortices of various origin and unsteadiness.
- **Direct-contact condensation.** A DBA, multi-phase issue related to the primary circuit and containment. This phenomenon is present in several PWR scenarios (e.g. two-phase PTS) when cold water is injected into steam environment or when hot steam enters a pool with cold water. Condensation efficiency depends on turbulent mixing and possible gravity-driven circulation. Two-phase CFD should be able to provide adequate closure laws for lumped parameter models and/or system codes. Multi-scale nature of this process requires a tool able to take into account macro-scale (pool), meso-scale (region around the jet) and micro-scale (region around interface between the bubble and the liquid) phenomena to predict condensation rates with sufficient accuracy.
- **Bubble dynamics in suppression pools.** A DBA, multi-phase issue related to the primary circuit and containment. This issue is closely related to the direct-contact condensation issue. Accurate modelling is necessary to avoid steam by-pass into the vapour space leading to over-pressurization.
- **Behaviour of gas/liquid surfaces.** An operational, multi-phase issue, related to the primary circuit and containment. Behaviour of water levels in reactor pressure vessel, accumulator, and suppression pools may be important for some scenarios. CFD allows treatment of the phases as separated fluids and actual position of interface can be tracked during the transients.
- **Special considerations for advanced reactors.**

The Writing Group 3 produced a list of two-phase issues, which contains some issues from the list above, but also some specific phenomena. The complete list is reproduced here without further comments, since this presentation will focus mainly on single-phase issues (very detailed description of the selected two-phase cases can be found in Ref. 3):

- **DNB, dry-out and CHF investigations.**
- **Subcooled boiling.**
- **Two-phase pressurized thermal shock.**
- **Direct contact condensation: steam discharge in a pool.**
- **Pool heat exchangers, thermal stratification and mixing problems.**
- **Erosion, corrosion and decomposition.**
- **Containment thermal-hydraulics.**
- **Two-phase flows in valves, safety valves.**
- **ECC by-pass and down comer penetration during refill phase of a LBLOCA.**
- **Two-phase flow features in BWR core.**
- **Atmospheric transport of aerosols outside containment.**
- **DBA reflooding.**
- **Reflooding of a debris bed.**
- **Steam generator tube vibration.**
- **Upper plenum injection.**
- **Local 3D effects in singular geometries.**
- **Phase distribution at inlet and outlet headers of steam generators.**
- **Condensation-induced water hammer.**
- **Components with complex geometry – separators – dryers.**
- **Pipe flow with cavitation.**
- **External reactor pressure vessel cooling.**
- **Behaviour of gas/liquid interfaces.**
- **Two-phase pump behaviour.**
- **Pipe break – in-vessel mechanical load.**
- **Specific features in advanced PWR.**

These lists are quite long and not all items are supposed to be taken into account in near future. Also assessment bases for them are very different. In order to improve this situation, the Writing Group 2 proposed an OECD/NEA International Workshop on the Benchmarking of CFD Codes for Application to Nuclear Reactor Safety to be organized in Garching (Germany), 5-7 September 2006. Presentations on CFD simulations with strong validation component and experiments providing data suitable for CFD validation, specifically in the area of NRS are requested. Emphasis is placed on single-phase phenomena and separated flows, but there is scope for some papers dealing with high-quality multi-phase experiments and multiphase CFD validation exercises following BPGs. Detailed information will be distributed to nuclear community probably next week, extended abstracts should be ready until November 30, 2005. After this workshop, the assessment matrix will be supplemented with new data.

Assessment activities described above will produce new ground for identification of gaps in present CFD technology. One of the main problems of application of CFD to nuclear reactor safety problems is transient nature of these problems. Experience gained so far shows lack of experimental data against which to validate time dependent CFD calculations. In addition, transient simulations are often so burdensome for Best Practice Guidelines techniques to be strictly applied. If a mesh with N computational cells is used, the run-time for the CFD code should scale with N^5, where the constant of proportionality, among other things, depends linearly on the total simulation time, which can be very long. So, parallel machines or clusters of machines accessed in parallel have become the mainstream of CFD simulations.

Modelling of turbulence is another source of uncertainty. No known model of turbulence (probably with the exception of the Navier–Stokes equations themselves) is general enough to be recommended for all situations. In the two-phase problems, the situation is even worse. Large Eddy Simulation (LES) or, in case of flows with solid walls, the Detached Eddy Simulation (DES) appear as possible future compromise between current engineering models based on the Reynolds-averaged Navier–Stokes equations (RANS) and computationally excessively demanding Direct Numerical Simulations (DNS). Certainly, more research, development and validation effort is required in this area.

Several NRS issues from the lists above require coupling of a CFD code with system, component, structure, neutronics or chemistry code. Examples are boron dilution issue (coupling with neutronics code), or PTS and thermal stripping issues (coupling with structure code). Some of the known examples are CFD neutronics coupling between STAR-CD and VSOP code, or TRIO_U and Monte-Carlo neutronics code (MCNP), or CAST3M code with CRONOS2 neutronics code. The case of cracks in the pipeworks of the French Civaux Unit 1 was simulated with CFD code Saturne, coupled with thermal code SYRTHES and thermo mechanic code Aster. Some type of coupling of a CFD code and a system code was also attempted; FLUBOX/ATHLET or FLUENT/RELAP5 coupling being the examples of coupling of codes with the same physics (thermal-hydraulics), but different scales (macro-scale system code and meso-scale CFD code).

4. CONCLUSIONS

The Writing Groups recommended creation of an internally complete document on Best Practice Guidelines for use of CFD in nuclear reactor safety analyses, and a set of application specific documents. These documents will be available on a website, maintained by NEA.

The Writing Groups also selected those NRS issues, where application of CFD techniques can enhance understanding and/or increase accuracy of predictions of thermal-hydraulic analyses. From the selected issues, mainly pressurized thermal shock, boron dilution and CHF were selected for simulations performed within EU-sponsored projects ECORA, FLOMIX-R, and NURESIM. Gaps in the technology base and the need for further development were identified. An International Workshop on Benchmarking of CFD Codes for Application to Nuclear Reactor Safety will be organized in September 2006 in order to evaluate and enhance available assessment matrix.

Current state-of-the-art of two-phase CFD simulations were reviewed and needs for additional experimental and numerical validation were identified. It was recommended to organize a new workshop on instrumentation with special emphasis on new local techniques required for two-phase CFD tool validation. It was also recommended to organize a series of benchmarking exercises for existing two-phase CFD tools and three tests were selected.

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