Workshop on "Benchmarking of CFD Codes for Application to Nuclear Reactor Safety (CFD4NRS)"

Executive Summary

BACKGROUND

Computational Fluid Dynamics (CFD) is to an increasing extent being adopted in nuclear reactor safety analyses as a tool that enables specific safety relevant phenomena occurring in the reactor coolant system to be better described. The Committee on the Safety of Nuclear Installations (CSNI), which is responsible for the activities of the Nuclear Energy Agency that support advancing the technical base of the safety of nuclear installations, has in recent years conducted an important activity in the CFD area. This activity has been carried out within the scope of the CSNI working group on the analysis and management of accidents (GAMA), and has mainly focused on the formulation of user guidelines and on the assessment and verification of CFD codes. It is in this GAMA framework that the present workshop was organized and carried out.

Computational methods have supplemented scaled model experiments, and even prototypic tests, in the safety analysis of reactor systems for nearly 30 years. During this time, very reliable codes have been developed for analysing the primary system, and similar programs have also been written for containment and severe accident analyses. However, many traditional reactor system and containment codes are modelled as networks of 1-D or even 0-D cells. It is evident, however, that the flow in components such as the upper and lower plena, downcomer and core of a reactor vessel is essentially 3-D in nature. Natural circulation, mixing and stratification in containments is also 3-D, and representing such complex flows by pseudo 1-D or 0-D approximations may lead to erroneous, and not necessarily conservative, conclusions. CFD has the potential to handle geometries of arbitrary complexity, and is poised to fill this technology gap for single-phase applications, though considerable further development of closure relations will be necessary before multi-phase Nuclear Reactor Safety (NRS) applications may be approached with confidence using CFD.

Traditional approaches to NRS analysis using system codes for example have been successful because a very large database of phasic exchange correlations has been built into them. The correlations have been formulated from essentially 1-D special-effects experiments, and their range of validity well scrutinised. Data on the exchange of mass, momentum and energy between phases for 3-D flows is very sparse in comparison. Thus, although 1-D formulations may restrict the use of system codes in simulations in which there is complex geometry, the physical models are well-established and reliable, provided they are used within their specified ranges of validity. The trend has therefore been to continue with such approaches, and live within their geometrical limitations.

For containment issues, lumped-parameter codes include models for system components, such as recombiners, sprays, sumps, etc., which enable realistic simulations of accident scenarios to be undertaken without excessive computational costs. To take into account such systems in a multi-dimensional (CFD) simulation remains a challenging task, and attempts to do this have only recently begun, and these in dedicated CFD codes rather than in commercial, general-purpose CFD software.

The issue of the validity range of CFD codes for 3-D NRS applications has to be addressed before the use of CFD may be considered as routine and trustworthy as it is for example in the turbo-machinery, automobile and aerospace industries. However, the application of CFD methods to NRS-related issues is not straightforward. In many cases, even for single-phase problems, nuclear thermal-hydraulic flows lie outside the range of current computer capacity, especially in the case of long, evolving transient flows with strong heat transfer.

These issues were discussed in the group of experts designated by CSNI/GAMA to carry out the task of establishing an assessment matrix for CFD application to NRS, concentrating on single-phase phenomena. As part of this process, it was decided to organise an international workshop to promote the availability and distribution of experimental data suitable for NRS benchmarking, and to monitor the current status of CFD validation exercises relevant to NRS issues. The workshop would also cover two-phase aspects, and if the venture was successful, organisation of further workshops on this theme was envisaged.

SCOPE AND OBJECTIVES

The purpose of the workshop was to provide a forum for numerical analysts and experimentalists to exchange information in the field of NRS-related activities relevant to CFD validation, with the objective of providing input to GAMA CFD experts to create a practical, state-of-the-art, web-based assessment matrix on the use of CFD for NRS applications.

Numerical simulations with a strong emphasis on validation were welcomed in such areas as heat transfer, buoyancy, stratification, natural circulation, free-surface modelling, turbulent mixing and multi-phase flow. These would relate to such NRS-relevant issues as: pressurized thermal shocks, boron dilution, hydrogen distribution, induced breaks, thermal striping, etc. The use of systematic error quantification and Best Practice Guidelines was encouraged.

Papers reporting experiments providing high-quality data suitable for CFD validation, specifically in the area of NRS, were given high priority. Here, emphasis was placed on the availability of local measurements, especially multi-dimensional velocity measurements obtained using such techniques as laser-doppler velocimetry, hot-film/wire anemometry, particle image velocimetry, laser induced fluorescence, etc. A particular point of scrutiny for papers in this category was whether an assessment of error bounds and measurement uncertainties was included.

CONCLUSIONS AND RECOMMENDATIONS

There were 98 registered participants to the workshop to hear 5 invited talks and 39 technical papers. This is perhaps a good measure of the level of general interest in the workshop. The messages coming back to the organisers from the participants were that the workshop was well organised and that the subject material well chosen. As there was only a 60% success rate for the extended abstracts sent in to the organisers for acceptance, the quality of the papers was high, and the focus of them on the central issue strong.

The case for future workshops in the series was discussed openly during the final panel session. It was pointed out that 2/3 of the papers accepted for CFD4NRS were concerned with single-phase calculations and experiments, while 1/3 were dedicated to multi-phase issues. The ratio probably reflects the degree of maturity of CFD in the respective areas, but nonetheless suggests a growing acknowledgement of the role of multi-phase CFD in nuclear NRS issues.

Following on from this observation, CEA proposed a follow-up meeting, perhaps hosted by CEA Grenoble, in which the ratio of single-phase to two-phase papers would be inverted, and would expand the area of advanced instrumentation needed for providing local data needed to validate the models currently being proposed for multi-phase CFD. The suggestion received encouraging remarks from the audience. It was also generally agreed that the frequency of future workshops should be 2-3 years, allowing sufficient time for the technology to advance, and minimise the chance of overlap with the material presented at CFD4NRS.

The Organising and Scientific Committees had discussed at an early stage whether the editor of an appropriate archival journal should be approached in regard to offering publication of selected papers from the workshop in a special issue of the journal. On balance, it was considered that it would be too great a risk to an editor for a first-of-a-kind conference with an untried format. It therefore came as a bonus that Professor Yassin Hassan, co-editor of Nuclear Engineering and Design, and a participant at CFD4NRS, would make just this suggestion. The offer has been followed up, and about 25 authors of technical papers and 3 invited speakers have expressed interest in this proposal. Again, the offer reflects the high quality of the presented material, and the general level of interest in what the workshop aimed to achieve. It is anticipated that the special issue of NED dedicated to CFD4NRS will appear early in 2007.

Clear recommendations to come out of the workshop for the continuing use of CFD methods in NRS issues are listed below.

- Best Practice Guidelines should be followed as far as practical to ensure that CFD simulation results are free of numerical errors, and that the physical models employed are well validated against data appropriate to the flow regimes and physical phenomena being investigated.
- Experimental data used for code validation should include estimates of measurement uncertainties, and should include detailed information concerning initial and boundary conditions.
- Experimenters involved in producing data for validating CFD models and/or applications should collaborate actively with CFD practitioners in advance of setting up their instrumentation. This interface is vital in ensuring that the information needed to set up the CFD simulation will actually be available, the selection of "target variables" (i.e. the most significant measurements against which to compare code predictions) is optimal, and the frequency of data acquisition is appropriate to the time-scale(s) of significant fluid-dynamic/heat-transfer/phase-exchange events.
- This workshop proved to be a very valuable means to assess the status of CFD code validation and application. Specialised workshops of this type should be organised at suitable time intervals also in the future, in order to maintain continuity, monitor progress, and exchange experiences on CFD code validation and applications.

Summaries of invited lectures and technical sessions are given at the ends of the Chapter 3 Chapter 4 respectively. The organisational aspects are outlined in Annex I, and the list of participants is given in Annex II.