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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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Experiments and CFD Code Application to Nuclear Reactor Safety (XCFD4NRS)

WORKSHOP PROCEEDINGS

Grenoble, France
10-12 September 2008

This report only provides the list of presentations and the summary of the technical sessions.

The full presentations or papers are available only in electronic form.

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made of senior scientists and engineers, with broad responsibilities for safety technology and research programmes, and representatives from regulatory authorities. It was set up in 1973 to develop and coordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The committee's purpose is to foster international co-operation in nuclear safety amongst the OECD member countries. The CSNI's main tasks are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and research consensus on technical issues; to promote the co-ordination of work that serve maintaining competence in the nuclear safety matters, including the establishment of joint undertakings.

The committee shall focus primarily on existing power reactors and other nuclear installations; it shall also consider the safety implications of scientific and technical developments of new reactor designs.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA) responsible for the programme of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health (CRPPH), NEA's Radioactive Waste Management Committee (RWMC) and the NEA's Nuclear Science Committee (NSC) on matters of common interest.

Acknowledgment

The NEA Secretariat wishes to express its sincere thanks to Dr. Dominique Bestion (CEA-Grenoble, France) for his distinguished services as General Chair of the XCFD4NRS, and to the CEA-Grenoble for having hosted it.

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 OECD 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 (WGAMA), and has mainly focused on the formulation of user guidelines and on the assessment and verification of CFD codes. It is in this WGAMA framework that a first workshop CFD4NRS was organized and held in Garching, Germany in 2006.

Following the CFD4NRS workshop, this XCFD4NRS Workshop was intended to extend the forum created for numerical analysts and experimentalists to exchange information in the field of Nuclear Reactor Safety (NRS) related activities relevant to Computational Fluid Dynamics (CFD) validation, but this time with more emphasis placed on new experimental techniques and two-phase CFD applications.

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 WGAMA CFD experts to create a practical, state-of-the-art, web-based assessment matrix on the use of CFD for NRS applications.

The scope of XCFD4NRS includes:

- Single-phase and two-phase CFD simulations with an emphasis on validation in areas such as: boiling flows, free-surface flows, direct contact condensation and turbulent mixing. These applications should relate to NRS-relevant issues such as: pressurized thermal shocks, critical heat flux, pool heat exchangers, boron dilution, hydrogen distribution, thermal striping, etc. Discussion of validation of the CFD tool, use of systematic error quantification and Best Practice Guidelines (BPGs) was encouraged and considered in the paper review process.
- Experiments providing data suitable for CFD validation, specifically in the area of NRS. These should focus on local measurements using multi-sensor optical or electrical probes, laser-doppler velocimetry, hot-film/wire anemometry, particle image velocimetry and laser induced fluorescence. Papers should include a discussion of measurement uncertainties.

Conclusions and Recommendations

There were over 140 participants to the XCFD4NRS workshop to hear 5 invited talks, 3 talks on OECD-CSNI activity related to CFD, 44 technical papers, and to see 15 posters. This is about 40% increase with respect to the previous CFD4NRS held in Garching in 2006, and this confirms that there is a real need for such workshops. The objectives that 2/3 of the papers be concerned with two-phase issues and 1/3 dedicated to experimental techniques and CFD grade experimental data were reached. Many participants sent the message that the workshop was well organised.

USA was candidate to host a follow-up meeting, organized by US-NRC (confirmed by NRC a few days after the workshop). The suggestion received encouraging remarks from the audience during the discussion at the panel session. KAERI also proposed to host and organize a future workshop. A great majority of participants considered they would be interested in attending a follow-up workshop within two years.

Comments were made during the panel session on the content of XCFD4NRS. It was considered that some contributions were not directly related to the nuclear safety. Another comment suggested that such workshops should be a forum to discuss novel approaches but one must also keep in mind that the end users are people from the nuclear safety. There was a consensus on the need to keep a high quality of papers. It was also suggested to promote international benchmarks for CFD.

Both CFD4NRS and XCFD4NRS workshops proved to be very valuable means to assess the status of CFD code capabilities and validation, to exchange experiences in CFD code applications, and to monitor progress.

There was again an offer to publish selected papers from the workshop in a special issue of the Nuclear Engineering and Design (NED) Journal. It was also mentioned that the special issue devoted to CFD4NRS received a very high number of visits on the journal website and a lot of papers were downloaded. Session chairmen will make a selection of papers to be submitted to the NED Journal. It was anticipated that the special issue of NED dedicated to XCFD4NRS would appear early in 2009.

The following additional comments were made:

- Current capabilities of two-phase measurement techniques are still too limitative for CFD validation. Further efforts are required to develop more advanced techniques, such as X-ray PIV, and international cooperation is necessary to support the high cost of development.
- Most of CFD codes are commercial and do not offer a full transparency with access to sources, which may be a problem from a regulation point of view.
- Application of CFD to Nuclear Safety requires that code uncertainties are determined, as they are now for system codes.

The participants made the following recommendations:

- One should keep a close link between people developing experimental techniques and performing validation experiments, and people developing CFD models and codes.
- Best Practice Guidelines should still be promoted, which requires that they are further developed and made more specific to each application. For two-phase CFD the establishment of Guidelines on the choice of the physical models depending on the phenomena being investigated has to be considered as a long term activity.
- Experimental techniques should be further developed to provide CFD-grade data for validating CFD models, including estimates of measurement uncertainties.
- A new item should be added in the scope of the workshop: the development and application of uncertainty evaluation methods for CFD codes

Summaries of the technical sessions are given at the end of Technical Sessions part. The organisational aspects and paper selection are outlined in Annex I, and the list of participants is given in Annex II.

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C. Chauliac, (CEA, France)

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V. Teschendorf (GRS, Germany)

Single Phase CFD Simulation and Experimental Validation for Advanced Nuclear System Components
Y. Hassan (Texas A&M, USA)

Modelling and Measurement of Interfacial Area Concentration in Two-phase Flow
T. Hibiki (Purdue Univ. USA)

Advanced fine scale modelling of two-phase flow
S. Banerjee (City University of New York, USA)

Experimental Techniques for Heavy Liquid Metals
T. Schulenberg (Karlsruhe Institute of Technologies, Germany)

Summaries of the Activities of GAMA Writing Groups on CFD

Best Practice Guidelines for the use of CFD for NRS applications
J.H. Mahaffy (Penn State Univ. USA)

Assessment of CFD for NRS
B. Smith(PSI, Switzerland)

Extension of CFD use to two-phase NRS issues
D. Bestion(CEA-Grenoble, France)

Technical Sessions

Session HOR: Horizontal Flow - Pipe Flow

HOR-01: Modelling free surface flows relevant to a PTS scenario: comparison between experimental data and three RANS based CFD-codes. Comments on the CFD-experiment integration and best practice guideline
Y. Bartosiewicz, J.-M. Seynhaeve, C. Vallée, T. Höhne, J.M. Laviéville

HOR-02: Nuclear Magnetic Resonance: A new tool for the validation of multi-phase multi-dimensional CFD codes
H. Lemonnier

HOR-03: Experimental investigation of stratification phenomena in horizontal two-phase flows for CFD validation
M. Marchand, M. Bottin, J.P. Berlandis, E. Hervieu

HOR-04: Numerical modelling of direct contact condensation in transition from stratified to slug flow
L. Štrubelj, I. Tiselj

HOR-05: Experimental CCFD grade data for stratified two-phase flows
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Session AC: Accident Analysis

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Krepper, G. Cartland-Glover, A. Grahn, F.P. Weiss

AC-02: Fluid-structure interaction analysis of large-break loss of coolant accident
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AC-03: Simulation of a gas jet entering a failed steam generator during a SGTR sequence: validation of a FLUENT 6.2 model
C. López del Prá, F. J. S. Velasco, L. E. Herranz

AC-04: An approach to numerical simulation and analysis of molten corium coolability in a BWR lower head
C. T. Tran, P. Kudinov and T. N. Dinh

AC-05: Debris transport analysis related with GSI-191 in advanced pressurized water reactor equipped with containment refuelling water storage tank
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AC-06: Data obtained at high coolant parameters suitable for validation of 3D models
B.A. Gabaraev, E.K. Karasyov, O.Yu. Novoselsky, S.Z. Lutovinov, L.K. Tikhonenko, Ye.I. Trubkin, A.V. Shishov

Session PTS: Pressurized Thermal Shock - Direct Contact Condensation

PTS-01: Status of a two-phase CFD approach to the PTS issue
P. Coste, J. Pouvreau, J. Laviéville, M. Boucker

PTS-02: FLUENT analysis of a ROSA cold leg stratification
T. Farkas, I. Tóth

PTS-03: CFD analysis of a turbulent jet behaviour induced by a steam jet discharge through a single hole in a subcooled water pool
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PTS-04: PIV measurement of turbulent jet and pool mixing produced by a steam jet in a sub-cooled water pool
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PTS-05: On the modelling of bubble entrainment by impinging jets in CFD simulations
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MIX-02: Experimental studies and CFD calculations for buoyancy driven mixing phenomena
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MIX-03: Experiments on slug mixing under natural circulation conditions at the ROCOM test facility using high resolution measurement technique and numerical modelling
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N. Kimura, K. Hayashi, H. Kamide

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Summaries of Technical Sessions

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SUMMARIES OF TECHNICAL SESSIONS

Session HOR: Horizontal Flow – Pipe Flow
(Chairmen: Chul-Hwa Song and T. Watanabe)

In the Session HOR, three papers were purely experimental studies and two papers presented both experimental and numerical studies.

In the experiment by Marchand et al. (HOR-03), velocities and void fraction have been measured in a horizontal pipe with several flow regimes including bubbly and stratified flows in air-water conditions; Vallee et al. (HOR-05) also investigated steam-water counter-current flow to simulate a hot-leg model with steam generator inlet plenum. Area-averaged velocity and void fraction in air-water pipe flows have been measured using a nuclear magnetic resonance (NMR) method by Lemonnier (HOR-02), and eddy diffusivity and dispersion coefficient were obtained. All these experimental works were performed for producing experimental data, which will be used for the development and validation of CFD codes and models. Measurement uncertainties were not systematically determined but some effort was noticed to compare several measurement techniques when possible.

Numerical simulations using the NEPTUNE-CFD code have been performed for condensation in counter-current steam-water stratified flows by Strubelj and Tiselj (HOR-04), and also for slug formation in air-water stratified flows by Bartosiewicz et al. (HOR-01). Such stratified to slug flow regime transitions were shown to be simulated well.

The noticeable point indicating the current status in this session is that two simulations and two experiments were for the development of the NEPTUNE-CFD code, whereas the CFX code was mostly used for simulations of horizontal or stratified flows in the previous CFD4NRS in 2006. For development of two-phase CFD codes, modelling of the interfacial momentum and heat transfers including turbulent parameters near the interface are of importance and further studies are still necessary.

Although precise measurements have been conducted in the experiments, the importance and difficulties in the measurements of local and instantaneous values of variables near the interface were pointed out, and the size effects and the setting of the boundary condition were also discussed. These points should be carefully taken into consideration in the experiments.

It seems that the Best Practice Guideline (BPG) have been better considered in numerical simulations when compared with the previous workshop. It has been shown in this session that the flow transitions in horizontal flows could be simulated well for simple cases. Validations for more complicated flow situations including integral scale phenomena and bubbly/stratified/slug transitions would be desirable.

Session AC: Accident Analysis
(Chairmen: N. Seiler and T. Morii)

This Session on Accident Analysis gathered various research subjects, such as insulation debris transport phenomena in water flow, Fluid Structure Interaction (FSI) related to the early phase LBLOCA, specific problems for severe accidents such as Steam Generator Tube Rupture, and molten corium coolability.

As these subjects are very different from each others, it is difficult to draw a general conclusion, but it appears that, with the progress of computer power, some CFD simulations of these accidents are now feasible.

Modelling used in the CFD codes seems to be mature enough to be applied to accident analysis issues and the presented works have shown some promising results. Simulations of a free surface and two phase flows configurations have been addressed in case of a recirculation sump blockage issue occurring either in Korean advanced nuclear power plant or in a PWR. Two ways to compute the two phase flows have been considered: a VOF method or an Euler/Euler approach. Considering the latter way, an important work has been fulfilled to validate the required modelling and also to adjust the model parameters. Other presented studies dealt with single phase flows simulated by commercial codes. The SGTR as well as the corium coolability problems have been addressed using the FLUENT code whereas, in the FSI problem, the thermal hydraulic part was simulated by the Star-CD code.

Regarding the corium coolability in a BWR, a new simplified model has been developed, called the Phase-change Effective Convectivity Model. Further improvements are still foreseen and in progress such as the accounting of entrained gaseous bubbles influencing the fibre sedimentation in case of insulation debris transport phenomena in water flow or the stratification of corium.

All presentations have included experimental validation and shown good agreement between calculation results and experimental data. A paper presented new data obtained in 5000 flow conditions of flashing, sub-cooled or saturated water, as well as critical flow data at pressures up to 9.3 MPa. The available data for codes validation are pressure differences and flow rate under single phase conditions, and critical flow rates as a function of inlet sub-cooling and pressure.

The BPG of the OECD GAMA seem to have been quite well followed and, simulation results have been validated against well instrumented and dedicated experiments. Some experimental tests have been used therefore to assess required unknown coefficients like drag force coefficient or other parameters. Furthermore, mesh quality has been checked. Meshing refinement and time discretisation as well as sensitivity studies to numerical methods and to closure models like the turbulence models, have also been carried out as recommended by BPG. However, the larger and more complex geometry of a real plant would need a larger number of grid points than that used for these studies focused on particular regions of the NPP.

Presentations proposed in this session have also underlined, on the one hand, the necessity to perform multi-physic simulations involving codes coupling in particular in Fluid/Structure field. On the other hand, it has been shown that validated CFD simulation results could be used as input data to derive required further modelling like 1D deposition model for SGTR accident.

Session PTS: Pressurized Thermal Shock & Direct-Contact Condensation
(Chairmen: M. Scheuerer and M. Andreani)

In this Session, 4 papers dealt with CFD analyses concerning applications to PTS in single and two-phase flows, to steam discharge in a pool, to air bubble entrainment caused by an impinging jet on the free surface, and to steam jet injected into a pool of sub-cooled water. Two paper presented experimental studies of a steam jet injected into a pool of sub-cooled water.

The paper PTS-01 presented a CFD modelling approach of a PTS two-phase scenario including the so-called Large Interface (LI) modelling, and the validation against air-water stratified flow data, and COSI steam-water condensation data. The NEPTUNE-CFD results obtained with the LI model were encouraging, the main trends being fairly well simulated, but further model improvement and validation require new experiments with more detailed measurements, in particular of the velocity field.

Simulations in paper PTS-02 with the FLUENT CFD code of an OECD ROSA test with temperature stratification in the cold legs and in the down comer during Emergence Core Cooling System (ECCS) injection followed BPG for the mesh generation, and for the quantification of numerical errors. Sensitivity tests investigated the effect of turbulence model and spatial discretisation schemes. A Reynolds Stress turbulence model provided the best results, and gave satisfactory agreement with data. Further improvements would require detailed velocity measurements.

The papers PTS-03 and PTS-04 present data and CFD analysis of steam jet condensation experiments with local velocities and temperatures measurements. Simulations with ANSYS CFX with a modified condensation model predicted well the turbulent jet region before the tank wall but failed to predict the flow at the upper and lower region after the jet collides with the wall. New experimental data investigate a free turbulent steam jet and pool mixing induced by the jet using non-intrusive optical Particle Image Velocimetry (PIV). The measuring techniques are given with an error analysis.

The simulation in paper PTS-05 of air entrainment caused by a jet impinging into a liquid pool is a difficult challenge for CFD since the corresponding physical process takes place at very small length scales. CFX11 simulations showed the influence of the drag model and of the algebraic interface area density model on the calculated gas entrainment.

The paper PTS-06 described an experiment of steam discharge into sub-cooled water with condensation. Simulations with NEPTUNE CFD using several 'established' condensation models, such as the Hughes & Duffey model, overestimate condensation rates by up to two orders of magnitude. The DNS-based model developed by Lakehal et al. (2008) yielded satisfactory agreement with data.

Overall the quality of the presentations in the PTS session was good, and there is progress which can be summarised as follows:

- There is visible progress in the area of PTS and DCC investigations. Useful experiments, especially for pool mixing and jet condensation have been reported. CFD modelling increasingly addresses two-phase flows with phase change. There are more applications of BPGs, and more separate validation of individual models and components. In the experiments the need to control boundary condition of the fluid domain has been recognised as an essential input for CFD calculations.

- However, the modelling of momentum, heat and mass transfer at the interface requires further work. Flows combining several interface configurations such as a bubble flow with a free surface are still poorly modelled. More general and/or specific local models need to be developed. Numerical robustness also seems to be an issue for some codes when applied to two-phase flow with condensation and evaporation.

- Available experiments still lack measurements of local velocity, turbulence, void fractions, bubble sizes and bubble distributions. Small scale/simplified experiments with better defined initial and boundary conditions are required for the CFD simulations. Although some measurement uncertainties were specified, systematic uncertainties are rarely given.

- Although BPG are increasingly applied many results are still presented on single-grids without convergence checks or other information about numerical errors. This makes model assessment very difficult and limits the usefulness of these models for industrial applications.

Session MIX: Mixing Issues
(Chairmen: B. L. Smith and D. Lucas)

A common feature of the papers, and an improvement since the last Workshop, was the general awareness that the application of Best Practice Guidelines (BPGs) is now a base requirement for CFD modelling. However, for purely practical reasons in terms of CPU overheads, there has to be some compromise in demonstrating mesh independence of solutions, for example for the VVER-1000 primary loop model, but maximum convergence of residuals was generally observed, and some sensitivity studies in regard to input parameters and (RANS) turbulence models. In contrast, most of the measured data are still being presented without error bars.

With the upgrade in computer hardware, and to a lesser extent software too (parallelisation), the CFD simulations are now becoming more adventurous, with attempts to model explicitly core bundles and those primary circuit components for which 3-D representation is needed. Calculations involving some tens of millions of meshes are now becoming more common, and being used to simulate transients too. However, meshes next to walls are still too large, even for the application of high Reynolds number turbulence models, and require further mesh refinement.

Several papers dealt with thermal mixing in T-junctions, and several sources of CFD-grade experimental data (meaning high resolution in space and time, instantaneous velocities and turbulence statistics) were identified. The need to employ advanced turbulence models (SAS, DES/LES) was noted, even for time averaged data; RANS predictions were generally poor. In addition, for thermal fatigue studies, it is necessary to capture the dominant turbulence scales. It was again emphasised, however, that mesh dependency remains an intrinsic feature of LES/DES approaches in physical space, since mesh refinement changes also the filter width of the resolved field. Hence strict application of BPGs is not possible.

Innovative measuring techniques for producing the comprehensive local velocity and temperature (or passive scalar) data needed for CFD code validation were evidenced in several papers. For example, a 10 kHz planar array sensor has the possibility to measure non-intrusively film thicknesses in opaque fluids, and signals from wire-mesh sensors enable contours to be drawn over an entire pipe cross-section. These data complement those traditionally made using thermocouples.

CFD-grade data collection (over 4000 points) was reported in the down comer section of the ROCOM test facility. There were also CFD-grade data collected in a vertical mixing test (VEMIX). A suspicion was advanced that outstanding discrepancies in boron dilution studies may be due more to the use of inappropriate turbulence models (to date RANS-based) than lack of geometric complexity in the models. The use of LES may be warranted, though if employed improvements need to be made in the near-wall treatment, the damping of maxima due to filtering, and a rationale for filter-width determination.

Session BOI: Boiling Flow, Bubbly Flow and critical heat flux
(Chairmen: E. Hervieu and M. Henriksson)

In the session BOI, six papers presented modelling & CFD calculations, three papers presented measurement techniques, and two papers presented experimental data bases.

Not so many authors referred to BPGs, and they were only partly applied in some cases. The main modelling issues dealt with bubbly flows and treated wall models, bubble dynamics, transport of interfacial area concentration, and turbulence modelling. A lack of validation data was pointed out for the wall heat transfer coefficient, the bubble departure diameter & frequency, the expressions of forces, and for the complex interactions between bubble dynamics and the turbulence. Source and sink terms for interfacial area concentration transport equations are still a major concern. K-ε models are used as « standard » but advanced models like RST are necessary to describe swirl.

A trend is noticed toward more complex geometries, which require mesh refinement and high CPU cost.

Measurement techniques tend to progress towards higher space and time resolution, toward complex geometries (pipes with internals) using non intrusive techniques, and toward representative thermal hydraulics conditions.

Innovative work was presented with photon attenuation (X, γ), and miniaturised wall electrical sensors. Such advances require long-time development.

Presentations revealed that large efforts have been devoted to the assessment of measurement techniques by comparison with reference techniques, the achievement of dedicated calibration procedures, and rigorous accuracy quantification.

Targeted 3D experimental databases dedicated to CFD validation were presented using either air/water or simulation fluids to represent steam-water flows. Experimentalists devoted large efforts to the accuracy quantification concerning the measured data, the operating conditions, and the documentation that makes the data usable.

There still remain lacks in bulk velocity measurement, near-wall measurement, in the use of representative geometries, and in the investigation of nominal reactor thermal-hydraulics conditions.

Session MS: Multiscale Analysis
(Chairmen: D. Bestion and Y Hassan)

This session, together with the lecture of Pr. Banerjee was a little different from the others. Here, CFD is not used directly for safety application but fine scale simulations are used for helping more macroscopic tools such as system codes or CFD with an averaged approach (RANS) to better model some specific small scale phenomena. Various techniques are used, such as DNS (Direct Numerical Simulation, LES (Large Eddy Simulation), with ITM (Interface Tracking Method), or ISS (Interface and Sub grid-Scale), which may bring precious information that available experimental techniques may not be able to provide.

Some progress has been obtained in the development and use of these two-phase fine scale approaches and the nuclear reactor safety community encourages research people to further develop and apply these tools focusing on some issues of interest. In the future, it might be proposed that people who develop closure relations for macroscopic approaches (system codes and CFD with an averaged approach) establish a list of small scale phenomena which are not well known, not measurable even with up to-date techniques, and which could be better known by such small scale numerical simulations. The nuclear safety community would give challenges to the scientific community for a better synergy between them and at the end for a better treatment of some safety issues.

Session CO: Containment thermal-hydraulics
(Chairmen: J. Mahaffy and E. Graffard)

In the session CO papers presented either experimental work or CFD applications to containment thermal-hydraulics, including mixing of steam-helium-air (helium being a substitute of Hydrogen), spray behaviour and effects, jet flows, condensation and re-vaporization, and catalytic recombiners. Some progress was observed since the last workshop:

- Gradual improvements are evident in two phase CFD tools such as NEPTUNE-CFD and GASFLOW
- Interesting new instrumentation concepts are reported in particular in the PANDA facility
- New numerical model are proposed for droplet evaporation at the wall

However problems are reported with liquid film modelling and condensing surfaces and questions are raised about modelling re-vaporisation of those condensate liquid films. It was also underlined that diameter variations of the droplets caused by collision, fragmentation, and coalescence, should be taken into account in future calculations.

There is a lack of separate effects experiments about sprays for validation of CFD application to containment simulations. If existing experiments cannot be applied to this issue, new experiments are needed. There was also an issue concerning potential problems with the reliability of gas concentration by measuring the sound speed, when a fog of condensing steam is present.

All papers showed some level of mesh sensitivity study and some attempts to justify numerical choices

Not attempt to quantify uncertainties was presented.

A better idea of scale effects in containments is still required, which is: certainly a real challenge!

Session CSG: Core and Steam Generators
(Chairmen: M. Andreani and F. Moretti)

The paper CSG-01 described an iterative process adopted at Westinghouse where CFD models are continuously improved and upgraded on the basis of new experimental information and increasing computational resources as well. Some experimental work and code assessment activity were also presented. The paper CSG-02 dealt with experimental investigations on flow mixing in the upper part of a VVER-440 coolant channel. In particular results from PIV and LIF measurement were shown, providing velocity and temperature distributions in the observed region and evidencing the effects of geometrical discontinuities on the flow field.

Papers CSG-03 and CSG-05 dealt with the CFD modelling of the SG of VVER reactors; the purpose of such activity was to obtain accurate information on the flow distribution over the SG tubes and thus help reducing the uncertainties connected with SOCRAT system code nodalisation. The paper CSG-04 was related to the experimental and numerical investigation of pressure losses across spacer grids. The effect of the inclination of the mixing vanes was considered as an experimental parameter. LES was used in order to understand and clarify the main features of the turbulent flow downstream of the spacer, then RANS calculations were performed and results were compared against measured data. Although very interesting, the presentations seem to be not fully representative of the large amount of work that is being done in the related fields of Core and SG simulation, and may not reflect the state-of-the-art. Therefore also the present comments have to be taken with the due care since they are based on a limited set of results.

In comparison with the last Workshop, some progress has been observed:

- Detailed validation methodology, including stepwise approaches, are being developed for the calculation of heat transfer in bundles, including spacer effects.
- Better data are available which include velocity fields.
- Some details such as the azimuthal distribution of heat transfer parameters are now being addressed and CFD-grade information of velocity fields are obtained.
- More and more attention is being paid to the estimation of experimental uncertainties and interpretation of the discrepancies between experimental data and CFD analyses.

All the works presented dealt with single phase flow and some difficulties related to turbulence modelling in complex geometries are reported. In relation to steam generator modelling, the large variety of accident conditions suggests to use various models for SG depending on the specific issue. There is probably a need to group such issues, for instance depending on water inventory on the secondary side.

A very interesting methodology was proposed to use data at low-Re number to compare qualitatively results obtained by CFD simulations for typical conditions (much higher Re number). However data in core conditions would be required for a proper code validation.

For the simulation of core and steam generator the current computer power basically prevent from applying existing BPG, because of the complex geometries: typically several million nodes are necessary (at least) for a detailed representation of the geometry and a refinement is basically impossible. Mesh refinement is possible only for special cases such as calculation of pressure losses across spacer grids.

Session AR: Advanced Reactors
(Chairmen: T. Schulenberg and F. Ducros)

The session AR presented experiments and CFD simulations related to gas cooled reactors and to Sodium cooled reactors.

Measurement systems for heavy liquid metals are still in an early stage of development compared with the advanced non-invasive methods used with air or water. There is certainly a lot to be done in future to develop reliable measurement systems.

Gas entrainment and two phase flow modelling has been the subject of 3 papers about sodium cooled reactors. An interesting and novel approach for the numerical study of such problems has been introduced by Kei Ito et al., which was discussed in the session. They used a high precision volume of fluid algorithm which was formulated for an unstructured mesh. The method is volume conservative and phase velocities are defined independently using volume fraction values. Comparison with a single bubbly experiment was used for verification. This example shows that the simulation of a free surface flow can still be improved significantly by a more precise volume of fluid approach.

Another general subject of discussion was the importance of computer hardware configuration and system programming to optimise CFD for large grid applications. A closer interaction of computer system developers with CFD users was recommended to make best use of existing hardware.

ANNEX I : ORGANISATION AND PAPER SELECTION

The Organising Committee and the Scientific Committee for the Workshop were formed from members of the three writing groups plus some other well known experts.

Organising Committee

Dominique Bestion, Commissariat à l'Energie Atomique, France, General Chair
Brian L. Smith, Paul Scherrer Institute, Switzerland, Co-Chair
John H. Mahaffy, Pennsylvania State University, USA, Co-Chair
Eric Hervieu, Commissariat à l'Energie Atomique, France
Martina Scheuerer, Gesellschaft für Anlagen-und Reaktorsicherheit, Germany
Han-Chul Kim, OECD Nuclear Energy Agency, France, Secretariat
Suk-Ho Lee, International Atomic Energy Agency, Austria, Secretariat
Bernard Faydide, Commissariat à l'Energie Atomique, France, Local Organiser

Scientific Committee

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Brian L. Smith, Paul Scherrer Institute, Switzerland
John H. Mahaffy, Pennsylvania State University, USA
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Yassin Hassan, Texas A&M, USA
Horst-Michael Prasser, ETH Zurich and Paul Scherrer Institute, Switzerland

The organising committee had the major responsibility for the practicalities associated with the setting up the workshop. Announcements were drawn up and circulated, and the criteria governing paper selection based on an extended abstract defined. An email list comprising nearly 750 addresses was the basis for distributing the first announcement. As the abstracts arrived, they were sent to members of the organising and scientific committees for evaluation. Of the 79 abstracts received, 3 were rejected as being unsuitable for the objectives of the workshop and invitations to write a full paper were sent out with only 44 for oral presentations and 32 for poster presentation at the workshop. In response, 59 draft papers were received and 17 papers withdrawn.

All the draft papers were distributed to the members of the Scientific Committee who sent them to two or more reviewers. All reviewed 59 papers were subsequently finalised by the authors. In addition, each of two keynote speakers (T. Schulenberg and T. Hibiki) provided a full-length paper to accompany his presentation.

Session chairmen were chosen from members of the organising and scientific committees. Summaries of the sessions have been subsequently written by them.

CEA-Grenoble hosted the workshop, and provided the infrastructure and staff necessary to support it. The local organiser took responsibility for all matters relating to local arrangements, including allocation and equipping of lecture rooms, the production of the hand-outs, for organising refreshments, lunches and evening programmes for delegates and accompanying persons, transport and accommodation, and for keeping the registrations and accounts in order.

The workshop took place over 2½ days from 10 to 12 September 2008.

ANNEX II - LIST OF PARTICIPANTS

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