SAFETY ISSUES CONCERNING NUCLEAR POWER PLANTS: THE ROLE OF CFD.

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Abstract

In Nuclear Reactor Safety, several issues concerning power plants deals with multidimensional fluid flow phenomena relevant to CFD applications. The objective of this paper was to analyze these issues and the contribution of CFD. Starting from some examples, in vessel mixing, PTS, containment hydrogen distribution, the limitations that usual codes are presenting and the expected benefits from the use of CFD codes have been derived. In order to be acceptable for nuclear reactor safety, numerical predictions should follow some requirements. Among those requirements, code validation a crucial one. It has been analysed within the more general experimental and analytical approach that the transposition question is demanding. The package of experiments required for assessment has been discussed. Different categories have been defined and role of each category has been discussed. Optimisation of the strategy for code development and code assessment has been proposed in order to answer to the key NRS transposition question.

1. INTRODUCTION

Several safety issues concerning nuclear power plants are known to be highly dependent on strong multidimensional flow behavior that ordinary system codes are quite unable to predict with sufficient confidence. Hence, during the last decade, there has been an increasing attempt to use single phase CFD codes or to develop two phase CFD codes in order to predict such situations. In 2002, meetings within IAEA and OECD framework, have been held to investigate at which conditions CFD can be used in nuclear reactor safety and several actions have been launched by CSNI which are reported in the present workshop.

2. SAFETY PROBLEMS WHERE CFD ANALYSIS IS NECESSARY

Several situations relevant to safety show a strong dependence on the detailed 3D behavior of fluid flows. A preliminary list of safety problems where CFD analysis could be of benefit was presented in [1]. A wide review of those safety problems has been undertaken within the CSNI framework [2] and provided an extensive catalogue of situations that we summarized in table 1.

In the following some examples will be selected and analysed concerning the reasons why CFD codes are needed with regard to the safety requirements on the nuclear power plants.

Table 1

Reactor deficiencies in normal operation:

Erosion, corrosion and deposition - Mixing: stratification/hot-leg heterogeneities - Heterogeneous flow distribution (e.g. in SG inlet plenum causing vibrations, HDR expts., etc.) - Thermal fatigue (e.g. T-junction)

Single phase accidental transients in the primary circuit

Boron dilution - PTS (pressurised thermal shock),

Severe accidents in the primary circuit

Induced break - Aerosol deposition - Lower plenum debris coolability - melt distribution

Containment fluid flow transient

Hydrogen distribution - Chemical reactions/combustion/detonation - Aerosol deposition - atmospheric transport (source term)

Specific two phase transients

Direct contact condensation - Behaviour of gas/liquid surfaces - Water hammer condensation - Pipe break, in-vessel mechanical load - Reflooding

BWR

Core instability in BWRs - Transition boiling in BWR - determination of MCPR - Recriticality in BWRs - BWR/ABWR lower plenum flow - Bubble dynamics in suppression pools

Special considerations for advanced (including Gas-Cooled) reactors

In vessel mixing

In case where an asymmetric loop operation is occurring, the question is to determine how much mixing will be obtained in the downcomer and in the lower plenum between the fluid of each loop so that to determine what are the conditions at the inlet of the core. In case of a slow transient, these fluid heterogeneities can be transported through the core where some mixing can take place. The different hot legs can then be fed with heterogeneous fluids that will be re-injected at the cold leg after passing through the loops.

There are various safety problems related to this phenomenon. Some of the most significant in terms of safety are the inherent boron dilution transients and the steam line break. In these scenarios, colder or non-borated water injected in the vessel from one loop arrives at the inlet of the core with more or less mixing with the water from the other loops. This mixing will determine the degree of boron concentration or the level of temperature which may induce when passing through the core recriticality returns and hence cladding failure and energetic fuel dispersion.

Present system codes, even if they use 3D modelling of the vessel (TRACE or CATHARE type), are unable to predict this mixing process without the addition of specific models. Generally the developed models rely on mixing matrices that are obtained from tests on reactor mock-ups generally in steady state. For each combination of loop parameters, mixing coefficients are determined by using the experimental results obtained on the reactor mock-ups. Such kind of models are used in the nuclear reactor safety (NRS) analysis, but their application raises a number of questions.

In the principle, any kind of model based on experimental results is a candidate for being applied in NRS applications at the condition that "confidence" in the model calculations will be obtained. In other words applicability of the model to predict the plant transient has to be demonstrated. To reach this objective a first concept is introduced which is that the model must be validated. This validation is obtained in a first step by assessing the model against experimental results. What is searched by this assessment is to demonstrate the capability of the model to predict the experimental results. When this step is achieved with success, the validation is not fully terminated, as what is really needed for the safety application is to demonstrate the capability of the model to predict the plant transient. A second concept is then introduced which is the representativity as regards to the plant of the experiment used for the assessment. Whenever the model is capable to predict plant representative test results, it can then be considered as being able to predict the plant itself. The representativity concept is a difficult concept that has been extensively discussed in the past. In order to make it simple at that stage, we will say that a representative experiment is an experiment where the phenomena are similar to the ones occurring in the plant and in the same parameter range. It comes out from past experience that representativity can never be completely achieved except when full-scale experiments are performed. The question of the representativity of the experiment against which the model is assessed has to be modified in the question: how the model can make the transposition from the experience to the plant taking into account the degree of representativity of the experiment and the inherent physical capabilities of the model for transposition (often called scaling capabilities).

Coming back to the in vessel mixing, the models based on mixing matrices are predicting the test results as they have been developed by correlating those results. Assessment can then be considered fulfilled within the correlation dispersion versus the experimental results. The main problem comes in fact from the question of the representativity of the experiments. Generally those experiments are mock-ups of the plant more or less obtained by simple homothetic ratios. The similitude with the plant that is generally transcribed by adimensional numbers cannot be fulfilled for all kind of phenomena that may occur. It is also quite difficult to represent some components such as the internals in the lower plenum that play a major role in the process. Moreover the experiments used for developing the mixing matrices are steady state experiments whereas the plant conditions are often transient conditions.

Analysing the applicability of the models based on the mixing matrices for deriving safety statements, one can say that those models are well representing the experiments but that those experiments can be quite far from being representative of the plant conditions. As the correlations are just the exact translation of the experimental results and as there is no physics added, the capability of the correlations to make a transposition is low and relies only on the more or less reduced degree of representativity of the experiments. In total, the applicability of those mixing models for NRS analysis is questionable. Decisions related to NRS using these mixing models are nevertheless taken. They need obviously to consider margins in the use of the results, which means that they are unable to treat correctly critical cases i.e.; cases which are near to the threshold where unacceptable consequences may occur. One interesting feature that has to be stated, is that discussions hold on this subject to arrive to NRS decisions, are often not considering at all explicitly the question of how far the experiments used for the mixing correlation are representative. This question should be indeed the key question.

In that situation, it is obvious that CFD can provide a big step forward. With CFD codes, there is an attempt to describe physically and mechanistically the mixing phenomena and particularly the phenomena that occur in the experiments on which the mixing matrices are based. Due to their physical basis, the CFD models can be expected to be able to perform some transposition from the experiments to the plant. CFD codes can obviously be considered as a mean to overcome the limitations of the usual simplified codes, but those CFD code capabilities have to be demonstrated. As it has just been explained, the CFD codes will have to follow a validation procedure that will comprise the assessment on the plant mock-up experiments and a strategy to provide a credible transposition. It is clear that this validation procedure for CFD codes will be heavier than for the simplified models. But this is clearly needed for getting a more valid answer to the safety requirements.

Pressurised thermal shocks (PTS)

Pressurized thermal shocks may happen in case of cold water injection in the course of an accident (LOCA, SGTR, main steam line break,…). This cold water may enter in contact with the hot walls of the vessel and may provoke a sudden temperature decrease (thermal shock) associated with severe related thermal stresses. The safety issue corresponding to the PTS is the vessel rupture and then the possibility to manage the following of the accident without going into the severe accident domain. This thermal shock may happen in single or two phase flows. The temperature decrease depends on the way the injected cold water mixes with the hot fluid and on the level of heat transfer between the more or less mixed cold water and the vessel.

In order to predict the PTS, it is first necessary to calculate the injected water characteristic properties. This can be achieved by the usual thermalhydraulic system codes, which physical models have some capabilities to predict mixing phenomena until the natural circulation is lost. Afterwards, these codes cannot be used further and one way to perform the evaluation is to use correlations derived from old CREARE tests that provided temperatures in the downcomer in function of the conditions in the loops.

Analysing how the validation requirements developed above are fulfilled for getting NRS useable predictions, it comes out that thermalhydraulic codes have generally been submitted to assessment on experiments and that CREARE correlations could be considered as assessed on the experiments from which they have been derived. The remaining questions are first the representativity of the experiments and second the capability of the models to make the transposition to the plant. Experiments used for code assessment are generally scaled down experiments on which it is difficult to comply with all the adimensional numbers. Similarity requirements are for example different for stratification and for jet impingement. Representativity for those experiments can then only be partial. Some full-scale tests exist (UPTF) which do not have to tackle the scaling down difficulty. However their problem is that they represent the German plant geometry and that the differences compared with other plants may modify largely the phenomenology observed. Representativity even for UPTF has to be carefully analyzed. For the CREARE correlation approach, nobody will certainly argue that the experiments are or can be representative of actual plants.

As regards the transposition capabilities of the models, the CREARE correlation approach presents the same kind of performance as, previously, the mixing matrices and the transposition capability is very poor if not null. Considering both representativity and transposition capabilities, CREARE correlation can only be considered as very approximate. The system code models are showing a different challenge. Their physical models are quite sophisticated and one could expect that they could be able to describe phenomena in the transposition. In fact when a model is matched to a certain experiment, it is not really able to predict an experiment in a different arrangement. This can be explained by the fact that the experimental results are sensitive to changes of some characteristics (geometrical or other) that are not at all (explicitly or through their effect) taken into account in the models. The models are then unable to predict by themselves the effect of those changes. As a consequence, obvious limitations may exist in their transposition capabilities.

The shortcomings of the system code models which are the cause of the observed limitations in their transposition capabilities come from the fact that phenomena to be described are governed by 3D, unsteady single or two phase flows. Turbulence, stratification, unsteady thermal coupling between structure and flow both in single and two phase and condensation in two phase are some of the phenomena which have to be taken into account. Complex geometries (downcomer upper plenum, connected pipes) and complex flow patterns (stratified, plume development,..) need to be precisely described. System codes are unable to predict all these features and CFD codes are obviously potential good candidates as they can include all the required models. In single phase flow, some results for PTS are or may be obtained. In two phase flow, CFD are at a very preliminary stage.

Nevertheless in the present state of the art, and although all their limitations, the thermalhydraulic system codes, within the flow conditions where they can be used, are certainly the present basic tools to be used for getting a practical answer to PTS safety questions. Even if approximate the predictions can be used in NRS with the provision either to limit themselves to qualitative trends or to consider sufficient safety margins or to have sufficient "permissive" uncertainty evaluation for taking into account the large epistemic sources of uncertainty. When CREARE correlations are the only possible answer because codes cannot be applied, they must be used but with even more caution.

Replacing the usual system codes and correlations by CFD code will not immediately solve the preceding questions. CFD codes have to be assessed and it has to be demonstrated that their transposition capability is real. From the phenomena that need to be included in the code, it can be imagined that the validation process may be quite complicated. In the document [2], it is proposed that two assessment methods should be used to be able to cover the complexity of the phenomena. This proposal is entering in fact in the more general question of the CFD code validation that we will discuss below (§ 4) and that will comprise much more steps. Those steps, even if they are not well defined and achieved today are certainly the way to reach a better answer to the safety PTS questions.

Hydrogen distribution

The 3rd example chosen to illustrate safety problems where CFD codes are necessary, deals with the containment behavior during accidents. In the hierarchy of safety issues, accidental containment behavior is very important as it is the last barrier with the environment and as consequently the releases and the radiological consequences will be dependent of its leak tightness. For any containment transient of interest for safety, the starting point is a discharge of the primary or secondary circuits into the containment. The multi-component multiphase flows induced in the containment by this discharge will determine the various loads that containment will have to sustain. An important possible threat on the containment comes from the presence of significant amount of hydrogen in this multiphase flow. Hydrogen can accumulate in some regions and can reach concentrations for which detonation or deflagration can occur. High pressure and temperature loads may result and may endanger the containment integrity. Consequently hydrogen distribution prediction becomes a specific sensitive issue. Hydrogen distribution cannot be separated from the general containment thermal hydraulics and its prediction requires a detailed knowledge of the multiphase flows in the containment, heat and mass transfers with the walls and the internals.

Multiphase flows in the containment either in the compartment configuration in the lower part or in the large free volume at the top (dome), are highly multidimensional. The physical models which are linked to the flow models are very complex, for example condensation or evaporation models on the walls in presence of various non condensable gas concentrations, condensation model on the sump surface and evaporation from the sump, models for heat and mass transfer with the spray droplets, modelling of pressure evolution due to venting through filters to the atmosphere, hydrogen combustion models in the passive auto catalytic recombiners (PARs).

The difficulties for developing those required physical models are known since decades. But the key issue that highly conditions the results is the representation of the topology for the flows. Different types of flow models have been used. The first type is the lumped parameter model based on a representation by control volumes and flow paths. The draw backs of such models are that inside a control volume the fluid properties are considered as "uniform" and only time dependent and that the momentum associated to the control volume is often assumed negligible (zero velocity assumption). The flow paths definition that have to be defined by flow areas, form and frictional pressure drops is arbitrary when in open space. Such models are very approximate for hydrogen distribution, the uniformity in the control volume lead to large over mixing which is not going in the conservative direction for hydrogen distribution issue. All the linked physical models are using the crude average control volume parameters whereas they should need local flow parameters on which they are physically depending. For flows in the flow paths some specific models can try to simulate specific phenomena such as counter current flows, slip flow..., but they are additives to a basic model not designed for this objective. From this picture, it is clear that the topology representation by lumped control volumes can demonstrate significant limitations.

The second type of modelling that has been developed can be named the field modelling [3]. This modelling used generally three fields i.e. liquid, vapour and droplets. The representation is obtained by a 2D/3D discretization of mass, energy and momentum equations in finite control volumes. A film flow model is used for condensing flows on the walls. Bulk vaporization and condensation are incorporated using generally homogenous equilibrium model. Sometimes turbulence is taken into account through a $K\,\varepsilon$ model. The noding can be quite detailed but not so much as with CFD. It provides a more local prediction of parameters that can be used for heat and mass transfer prediction. Counter current flows are obtained as solutions of the basic flow equations. A better prediction of physics is or can be potentially obtained compared to the lumped parameter models. This level of physics can be compared to the one of the system thermal hydraulic codes but with their well-known difficulties like for example the numerical diffusion, the modelling of steam condensation in presence of non-condensable or in very transient conditions.

The last way to model containment is by using CFD, which mainly starts from single phase codes with adaptations. The Navier Stokes equations are written for multiple gas species. Models such as bulk and wall condensation, interaction with spray, film flow, etc.. must be added to get all containment specific phenomena predicted. Those models can be more or less sophisticated going from the simple correlation wall function to the detailed description of phenomena inside boundary layers. The level of physics is similar to the one of field codes but can be potentially more sophisticated. CFD type codes have finer meshing capabilities that may reduce the numerical diffusion of the other codes. This may be essential to predict accurately temperature, velocity, concentration gradients which exist in some places in the containment and which may influence the overall containment behavior.

The three levels of modelling represented by lumped parameter, field, CFD, and in some codes a combination of these three levels can be used in NRS applications. However, the safety conclusions that are drawn should be different in nature.

As lumped parameter modelling has been used since several years, an extensive assessment has been performed. Consequently, it comes out [3] that the lumped parameter codes are making quite relevant predictions of the average parameters measured on the experiments against which the codes are assessed, like the average pressure history, the average steam and hydrogen content. Due to the averaging process, the transposition to the plant may be questionable. In particular it is well known that there may be large discrepancies when non-linear effects affect some key phenomena, figured often out by the fact that for non-linear function f(Xi) the average of the function is very different from the function of the average parameters Xi. In the transposition, these non-linear effects can vary significantly which may make the averaged parameters deviate from the real ones even if properly assessed on scaled down experiments. Moreover, the lumped parameter codes are, by essence, totally unable to predict local parameter profiles. For pressure, except for specific parts of the transient where there are high flow rates (for example at the beginning of the primary circuit discharge or at vessel melt through by the corium), the relatively low form and frictional coefficients leads to low pressure drops and the average value of the pressure may be representative. On the contrary, accumulation of steam and hydrogen can potentially take place at some localized positions and the local profiles may be significantly deviating from the average values. As hydrogen ignition and combustion is sensitive to local values, evaluation of hydrogen risk in NRS applications should take sufficient margins when based on the averaged values of hydrogen distribution provided by the lumped parameter codes. If the trends between average and local values are generally known in order to get margins (except if there are some opposite cross effects), there are very few elements in fact to judge whether those margins are sufficient.

Field codes and CFD type codes have intrinsically the capabilities to overcome the limitations resulting from the lacks in the topology description of the lumped parameter codes. The difficulty comes there probably from the level of assessment that needs to be much more detailed. In particular, several physical models have to be developed and should be assessed separately to be sure that the transposition is correctly performed. Physical developments, assessment and transposition are certainly the tasks where progresses are needed to consolidate the potential use of field and CFD codes for NRS applications on hydrogen distribution.

3. CFD CODE CONTRIBUTIONS TO NRS ISSUES - CORRESPONDING REQUIREMENTS

Simplified modelling: a first answer to NRS issues

On the three examples (in vessel mixing, PTS, hydrogen distribution) that have been previously described, simplified modelling (such as correlation type approach, lumped parameter approach, ..) has often been chosen as a first step for solving the corresponding NRS issues because not enough knowledge existed to carry on more detailed modelling that the complexity of phenomena would have normally needed. An other limitation in the application of this detailed modelling often came from the computational capabilities that are required and that current computers at the time the simplified modelling were developed, were unable to provide. Situation on this last point is changing continuously with the progress of the computer technology but it still remains a limiting factor as the desires and the needs of scientists are progressing concurrently to the computer capabilities.

It has to be recognized in general and it can be observed in particular in the three chosen examples, that the simplified modellings are often extensively assessed on experiments. The modellings are then able to reproduce with a certain accuracy experiments that normally are designed to be representative of the reactor. The problems are there twofold. First, due to the fact that all phenomena are not taken into account in the models, it often comes out that it is impossible to reduce below a certain level the divergences between calculational and experimental results. Secondly, except for some cases like full-scale core simulation experiment, it is very difficult and almost impossible to define completely representative experiments. Consequently the transposition to the plant is questionable, a good fit of the model on an experiment being not a guarantee of a good prediction on the plant.

Whatever the code capabilities are, NRS issues often require immediate practical answers particularly in the licensing domain. The answers have then to be adapted in function of the code capabilities. A very common way in nuclear safety to reach practical answers from simplified modelling is to use conservative approaches. Conservatisms are claimed to be taken in order to cover the unknowns so that sufficient safety margins will be ensured. In order to define the conservatisms, sensitivity studies can first be used to determine in which directions parameters have to be modified in order the predictions to be conservative. Except for few cases, simplified modellings are able to give those directions. The next question is to determine the amount of conservatisms needed to cover the lack of knowledge corresponding to the simplified modelling. Generally conservatisms are checked on experiments used for assessing the modelling but as transposition was questionable for the modelling results, transposition is also questionable for the conservatisms. Therefore this makes quite difficult the judgement whether the conservatisms are sufficient. Moreover this makes impossible the rigorous determination of how conservative the results are. The only way to get some confidence in the chosen conservatisms is practically to increase them significantly. But increasing conservatisms induces often constraints on the power plant effectiveness and it is sometimes difficult to agree on what can be considered as a "reasonable" amount of conservatisms. By experience the conservatism problem is really never solved and is subject to transaction from time to time where the expert feeling plays an important role. An other way to try to cope with simplified modelling and to overcome the conservatism questions, is to evaluate uncertainties. Indeed, if no progress is made in the knowledge of the model simplifications, the basic question of the conservatisms and specifically of their transposition is transferred to the question of the determination of the epistemic uncertainty related to the model simplifications and to the question of their evolution in the transposition. Here again sufficiently large uncertainty values should be taken in order to get sufficient confidence.

Need for more detailed physical modelling and validation for NRS issues

Transposition appears then as the key problem for answering NRS issues even if one has to acknowledge that this is not the question most frequently discussed when NRS choices and decisions are taken. To improve the transposition capability, which is obviously limited in case of simplified modelling, orientation towards more physical tools has to be taken. The expectation is, with sufficiently physical models, to obtain or to approach the true physical system behavior. Therefore it is anticipated thanks to the physics embedded in the models that the effect of changes in scale and in conditions from experiments to the plant can be predicted or better approached than with simplified modelling. An other goal is to obtain a best estimate prediction of the physical plant parameters and then an evaluation of the conservatisms that cannot otherwise be reached, for finally replacing the conservative approach by a best estimate approach with uncertainty evaluation [1].

Such an approach has been followed in the mid/late seventies in thermal hydraulics when the decision was taken to develop the present thermal hydraulic system codes (CATHARE, DRUFAN/ATHLET, RELAP5, TRAC). The problem was to replace the first generation codes (RELAP4 type) based at the very beginning on two phase homogeneous thermal equilibrium model. Because of their physical model limitations, these codes were used for accident studies in a conservative way (evaluation model, appendix K). The main question raised at that time was to confirm and evaluate the amplitude of the margins that were taken. For that it was recognized that the only way was to develop best estimate tools where the most advanced physics available at that time will be included and which will provide a good approximation of the real system behavior.

This step in the direction of a more detailed and physical modelling has been achieved by using the two fluid model. The peculiarity of this model was that, for the first time, the evolution of the individual phase flow parameters were mechanistically predicted by the modelling of the transfer laws (mass momentum and energy transfers from wall to fluid and between phases) instead of being determined by integral correlations between parameters. For example, the velocities of each phase instead of being connected by a slip correlation (for example drift flux), became the dynamic result of the physical phenomena which determine them that is the driving momentum forces expressed in the momentum equation and the resistance force expressed by the interfacial and parietal frictions. In the same way thermal non-equilibrium became the dynamic result of the non-equilibrium driving force (pressure drop, heating) and the resistance force expressed by the interphase mass transfer law (evaporation, condensation). It was expected that modelling by this way the physical mechanisms which are responsible of the flow evolution will provide better results in the transposition than the integral correlation adjusted on scaled down experiments. This new modelling was accompanied by new numerical methods mainly using 1D discretization that replaced the volume junction type noding. Only one code (TRAC) included in the early 80's a 3D modelling for the vessel with a porous medium two phase flow model and with a coarse meshing.

The validation of these advanced models has been an important task considered most often as integral part of the development. Large experimental programmes have been launched against which the codes have been assessed. Specific validation strategy has been defined in some programmes and followed in order to obtain a complete validation including transposition to the plant. The content of this strategy will be discussed in chapter § 4.1. Even if significant progress has been made in describing the physical phenomena and despite of the use of specific validation strategy, it can be said that some transposition problems still remain, essentially because scaled down experiments can never be completely representative (except full scale ones), because in every models even if they are quite sophisticated some simplifying assumptions must be made which introduce shortcomings and because the effect of these model shortcomings is very difficult to control in the transposition process.

CFD: a more detailed modelling approach, contribution to NRS issues and validation requirement

CFD codes approach is obviously in the following of the preceding evolution where more physical and more detailed modellings are developed in order to get rid of over conservative approaches or to get better confidence in transposition. For single phase flows, there are several cases in large capacities or at connections where multidimensional effects are predominant for the consequences on plant operation or plant safety (see table 1). In those cases, CFD, as it has been shown in the examples, is the unique way to describe physically multidimensionality of the single phase flows that other models try sometimes to predict with correlations. In two phase flows, multidimensional situations are generally experienced everywhere they occur in single phase flow but there are in addition several other cases to be considered as 1D situation in single phase flow, namely because of the irregular void fraction distribution would require, in two phase flow, multidimensional modelling. One has also to observe that most of the scaled down experiments on which the present second generation two phase flow codes are assessed, are mainly 1D experiment which are often completely non representative of the multidimensional effects occurring in the plant. Consequently, lack of multidimensional description in those last codes is certainly a basic drawback for their transposition capabilities. Some over shortcomings linked to the simplifying assumptions of the current two phase flow modelling have also to be reduced in order to be consistent with the multidimensional description of the flows. For example, average transfer laws used in 1D models have to be generalised in order to get local formulations. These transfer laws should be able to describe non-steady non-established flows including the various turbulence effects. All those objectives, which define what is called two phase CFD, are very ambitious, but this is clearly what is needed to make a significant step forward in pertinence of the prediction and in the transposition capabilities. Obviously this would need time to be developed and to become operational.

As for the preceding code generation, application of the new CFD type code generation will strongly depend on their validation. Probably new experiments will be needed, because codes will have to be assessed against new phenomena or combination of phenomena. Transposition from experiment to the plant will remain an open question, as the question of the complete representativity of the experiments will never be solved. Of course, one could expect due to the very fine description of the physics that the code transposition capabilities will be better than previously, but these capabilities will in fact only be revealed after extensive assessment showing that the basic detailed physical laws are sufficiently accurate and general. This will require specific care in the assessment strategy and will require time as new codes are often in their beginning of development less efficient than the preceding less physical ones.

4. CODE VALIDATION REQUIREMENTS AND STRATEGY

Use of codes for NRS application purposes requires that the applicability of the codes be demonstrated for the expected applications. The validation process intends to provide this demonstration and every time a new code is written and/or applied a validation plan has to be defined. The key problem in NRS for this validation is the question of transposition from the experiments to the plant. Specific strategy has then been used for the present thermalhydraulic system codes that will be discussed next. This transposition problem corresponds in fact to generic problems that are also encountered in numerical simulation of other physics cases and particularly for CFD. Consequently, what will be discussed next for the present thermalhydraulic codes can have a much wider application.

4.1. Code validation performed for thermalhydraulic system codes

Experimental and analytical approach

When a physicist has to predict the behavior of a physical system, his first normal approach is an experimental approach consisting in reproducing, observing, measuring and analysing the physical system behavior he has to predict. Two cases can occur for this experimental approach.

In the first case, it is possible to reproduce exactly the physical system, i.e. the system can be experimentally simulated at full scale or if some scaled down is necessary, the similarity laws are well known which allow to transpose results from reduced scale to full scale. In this case, experimental results can be used directly for predicting the physical system behavior, and provided that the experiments simulate all the operating conditions, the experimental results can be sufficient to answer the initial question of the system behavior prediction. Of course, numerical tools can be used to help for exploiting the experimental results in the applications. This may for example consist in correlating the results allowing by that way an easier interpolation between the experimental points. In NRS there are few examples entering in this fully experimentally representative case. One example is the case of the Departure from Nucleate Boiling (DNB) in the core. For DNB experimental investigation, core rod bundles can be simulated by full-scale electrical bundles with the exact geometry and with all the real components, grids, mixing devices, etc... The experimental results obtained on these electrical bundles are giving then exactly the plant core response to DNB. In order to make the plant prediction more practical, calculation tools have been written, first including completely empirical DNB correlations that were adjusted on the DNB experiments. Provided that those tools were used in exactly the same manner for the plant than for adjusting the correlation on the experiments, the plant prediction could be considered as completely valid. This of course does not prevent to develop detailed physical tools (even using CFD) to describe DNB for example in view of optimisation. Those detailed tools will have to be validated, but the difference with what will be discussed later is that at anytime an experiment can be run for getting the exact response.

Unfortunately, this first case in the experimental approach of the behavior of physical system is quite rare in NRS. Most often the second case is found that is the physical system cannot be reproduced experimentally at full scale, it must be investigated in scaled down experiments and the similarity laws are not well known. As it can be easily understood, this second case is quite common in NRS because plant accidents are mostly impossible to "simulate" at full scale and because, as two phase flow is involved in the themalhydraulic behavior, similarity laws have a lot of unknowns.

It has first to be noted in this second case that as similarity laws are not known and as in the scaled down process they cannot all be satisfied, the experimental responses on scaled down mock ups can never be assimilated to the real plant response. The consequence is that the plant behavior can only be evaluated by a combined experimental and analytical (code) approach. This approach includes three steps: a) experiments are performed to simulate as closely as possible in a global or partial way the plant transients, b) codes are developed and assessed on the experiments, c) the assessed codes are applied as basic tool for the transposition to the plant. In the following step a) and b) will be discussed.

Experimental programmes for code assessment

The starting point for defining the needed experimental programme for code assessment is to recognize that the system behavior is in fact resulting of the combination of several elementary phenomena. The problem is then first to identify those phenomena, secondly to study them experimentally separately and third to recombine them. This leads to three categories of experiments that have been distinguished and defined when in the late seventies the thermalhydraulic experimental programme for advanced thermalhydraulic system codes was launched. These categories were:

- The separate effect tests (SETs) where individual phenomena are simulated (for example critical two phase flow, water blowdown, counter current flows, phase separation, level formation, condensation, critical heat flux, blowdown heat transfer,….).

-The component tests where a global component is simulated because phenomena occurring in that component are so mixed that it will be difficult to have a detailed description and which will be consequently modelled in an integral way (for example primary pumps).

-Integral experiment tests (IETs) where the target is to get an experimental simulation of the complete plant system or of a significant part of the system (for example LOFT, LSTF, BETHSY, PKL,….). In the IETs all individual phenomena are reproduced together and their coupling simulated.

To identify the individual phenomena that have to be simulated in the SETs, the first method is to run integral experiment (IETs) especially when the physical domain has never been investigated. Analysis of experimental results on the IETs will demonstrate which phenomena should occur in the plant for the simulated transient and consequently which phenomena should be simulated in the SETs and modelled in the codes. IETs have then a first objective of phenomena identification (sometimes forgotten even if essential) besides the objective of providing data simulating the global system for checking the code capabilities (see next). The IETs are designed to represent as closely as possible the plant itself, which means that the similitude is chosen so that the predominant phenomena will be the same on the plant and on the integral experiment. This means that some knowledge of phenomena is needed for the IETs to be well designed whereas the IETs are needed to investigate which are the phenomena occurring. Iteration is then sometimes required for adapting the IETs for given transients in order to well identify and represent the phenomena. Example of such an adaptation is the integral loops that have been designed after TMI to simulate small break LOCA. As stratification becomes a predominant phenomena, Froude similitude was used in the new loops (BETHSY, LSTF, PKL) contrarily to the preceding loops (SEMISCALE, LOFT, LOBI) designed for simulating large break LOCA. This allows a better identification of the amplitude of the stratification phenomena which may occur in the plant and that should be properly described in the codes.

An other method to identify individual phenomena is the use of PIRT. This method is certainly very powerful when sufficient knowledge has been obtained in the domain. In a certain manner, it can save some IETs to be performed but it has to be noted strongly that it is unable to replace the entire IETs programme, as some may believe. This warning is all the more important that the physical domain is not so explored. There are examples in the severe accident domain where PIRT had built scenarios that had been later completely invalidated by tests on IETs (for example iodine chemistry, core degradation, ..). In thermalhydraulics, a lot of experience has been accumulated and the likelihood to find new individual phenomena to be described by the present codes is low. However, for the multidimensional aspects it cannot be excluded that IETs shall be necessary for investigating the individual multidimensional phenomena that may occur on the plant.

The motivation to simulate individual phenomena on SETs was primarily to be able to perform a useable experimental investigation. For that purpose, the experimental element to simulate had to be as simple as possible so that it will be understandable and so that the experimental results can be used for a comprehensive assessment of physical models. Going to the simplest level i.e. the individual phenomena was considered to be the best way to achieve the previous goals. SETs were to be designed so that enough experimental flexibility can be obtained for varying and controlling the experimental conditions. This was of course necessary to fulfil the physical model assessment objectives together with a detailed and numerous instrumentation that was often only possible on SETs. We have to recall that in the 70s'/80s' one of the limitation on the number of measurements was the data acquisition systems. The "localization density" of the measurements in IETs was then limited and only SETs reduced in scale were able to get the number of measurements necessary for detailed analysis and assessment.

An additional category of experiment is sometimes distinguished which is the analytical experiments (AETs). Those experiments are of the same type as the SETs but are more fundamental and more basic. Their use is mainly oriented to the physical model developments. This category has almost disappeared in the present NRS thermalhydraulic because probably the basic development of the presently used physical models is a task that has been performed some 30 years before. The experiments that could enter in this category are presently assimilated to SETs. It should be however interesting to consider this category in case of new model development.

Code development and validation process

As explained earlier, the four categories of experiments, analytical (AETs), separate effect (SETs), component and integral (IETs) have been defined to investigate experimentally as far as possible and with a systematic logic all what may occur on the plant. As we have also explained in the experimental and analytical approach discussion, experiments are not sufficient in most NRS thermalhydraulics cases to predict the plant system response and codes need to be used. In order to establish the capabilities of the code to predict the plant transients, codes are assessed on the set of experiments that have been previously defined. Depending of the experiment category, information obtained by assessment varies. Assessment on SETs will provide the capabilities of the code to predict each physical phenomenon separately. In the CATHARE French strategy, this assessment was called, in the late 70's, "qualification". Assessment on IETs will provide the capabilities of the code to predict phenomena all together and consequently their interaction and their coupling. As sometimes the IETs were performed at larger scale than SETs, assessment on IETs will provide for those cases the capabilities of the code to predict some change in scale. As assessment on IETs has different objectives than assessment on SETs, it was distinguished in the late 70's from the "qualification" by the wording "verification". As since that time the term verification has been differently defined by quality insurance people and also by CFD experts we will call it here "integral assessment" to avoid any confusion. It has to be noted that all teams have not immediately used the distinction between "qualification" and "integral assessment". For a long time SETs and IETs have been mixed in several code assessment strategies as it can be observed in the first CSNI thermalhydraulic validation matrix. This distinction is now accepted but still more or less used.

When a thermalhydraulic system code has followed the qualification process on SETs and the integral assessment on IETs, it has been validated in fact for all the conditions covered by the SETs and IETs package. As IETs cannot be completely representative of the plant, the real plant conditions differ inevitably from the IETs conditions and the code that has been assessed on IETs conditions cannot be considered as assessed on plant conditions. Of course IETs are designed in order to be as close as possible to the plant. This means that the similitude (a) for the dominant phenomena is preserved on the IET. But other phenomena will have their similitude (for example (b)) distorted in (b') in the IET. Code being assessed on conditions (a, b'), there is no scientific proof that it will work in conditions (a, b) but only presumption. This presumption will be more or less high, depending first on the IET representativity. The only way to increase this presumption is to check whether the physical models are capable to extrapolate from conditions (a,b') to condition (a, b). For that purpose a strategy of code development was defined in France for the CATHARE code. As SETs are dealing with separate effects, the physical models were developed and assessed (qualified) on SETs for which an extensive French package had been developed. The code version was then frozen and was submitted to the integral assessment on IETs. When discrepancies were found not acceptable during the integral assessment, the physical models were worked out again but on the SETs only and not tuned on the IETs. The new code version with the modified physical models was again frozen and checked on the IETs. When satisfying agreement was obtained, this agreement could be expected as a result of the "quality"/"pertinence" of the physical models. The physical models which was then able to predict the conditions (a, b') without any tuning on the conditions themselves could be expected to be able to predict with some confidence the condition (a, b). The application of this strategy has shown some practical limitations that are interesting to note. When discrepancies are found in IETs calculation, generally sensitivity studies are performed in order to determine which physical models are at the origin of the discrepancies and in which direction they should be modified. The following task of improving the physical models on the SETs may be influenced by those indications and the independence between qualification and integral assessment as planned initially is probably a little bit disturbed. Secondly planning constraints on code development makes that, sometimes, integral assessment has been a little bit anticipated before freezing the code version. This may also introduce interactions that are in contradiction with the principles of the defined strategy. In spite of those limitations, this strategy was probably the best that can be done and was certainly better than the tuning on IETs which had been realized for some codes and which is still applied in other NRS domains.

Of course this strategy does not solve entirely the question of transposition but it certainly contributes to its solution. In particular it will never solve the effect of the simplifying assumptions of the models that may strongly change the results in the transposition. For example and as CFD is the subject of this paper, a 1D model may give a good agreement on an IET which geometry is mainly 1D, but it will never predict accurately the plant if the plant presents strong multidimensional effects.

The NRS code development and validation is in fact entering in the case described in [4] where its validation domain does not cover its entire application domain. This is certainly the most difficult case in the numerical simulation of physical systems. The only way to overcome this difficulty (and never completely) is to rely on the high level and pertinence of the physical models. This level and pertinence should be so that, if assessed on the validation domain, they can be expected to be able to extrapolate outside the validation domain in the application domain. This highlights very strongly the importance of SETs and the importance of "qualification" of physical models. This highlights also the importance of all procedures in the code development and assessment process which will contribute to avoid any tuning on IETs as this tuning may "pollute" the extent of the conclusions we may draw from the comparison between codes and IETs. This shows also incidentally that the capability of a code to predict a type of plant transient cannot be estimated only by comparing the code on the same type of transients run on IETs but that the capabilities of the code in the prediction of individual phenomena simulated on the SETs have also to be considered. This mistake is unfortunately very common.

4.2. CFD code assessment for NRS applications

Experimental and analytical approach

The physical plant transients, which are foreseen to be predicted by CFD codes, belong clearly to the second case described previously where simulation by full scale experiment is hardly feasible and mostly impossible and where similitude laws for designing scaled down experiments have often a lot of unknowns. This stands as well as for single or two phase CFD. The plant transients which would be described by two phase CFD do not differ indeed on the principle from the situations treated by the system thermalhydraulic codes except that they are dealt with in a much more complex way. As a result, they belong to the same category of physical problems. For the situations relevant of prediction by single phase CFD, the similitude laws are, in general, much better controlled than in two phase but it remains some unknowns for specific topics that make the corresponding plant situations entering also in the second category.

As described in § 4.1., the prediction of the plant behavior for all those situations raises transposition questions and requires a combined analytical and experimental approach. As the physical issues do not really differ from the ones treated in system thermalhydraulics, the combined analytical and experimental approach should not be very different. In this approach, a series of experiments are first defined to simulate physically as closely as possible the plant transients. Those experiments are then used to develop and assess the codes. Applications on the plant are carried out with these assessed codes that constitute the main tool for performing the transposition to the plant.

Experimental programmes for code assessment

The objective of the experimental programme for code assessment is to cover as far as possible all situation and phenomena occurring on the plant. The application of the preceding strategy to define this experimental programme is one way to proceed on a physical basis and should lead to the same categories of experiments:

- The separate effect tests (SETs), which are needed in order to investigate individual phenomena expected to occur in the plant and in order to provide data for assessing the CFD code models.

- The analytical tests (AETs), which can be distinguished from the separate effect tests by the fact that they are more fundamental and basic tests used for developing the basic CFD turbulence and linked models

- The component tests, which could be necessary when specific assessment is needed for complex parts such as for example some internal structures.

- The integral tests (IETs) simulating the reactor or a significant part of it and which will be necessary for assessing the capabilities of the CFD code to predict the global behavior, to combine individual phenomena and to predict their interaction.

It is clear that the IETs to be used should focus and comprise measurements relevant to the phenomena to be modelled by CFD for example, flow field distributions of pressure, temperature, velocity components, concentration, surface heat flux,…. The IETs needed for CFD may differ from the IETs defined for thermalhydraulic system codes. They will encounter same types of similitude problems when compared to the plant but as they focus on some more detailed phenomena, it may lead to different similitude compromises.

Identification of individual phenomena to be simulated in the SETs and which should be modelled by the CFD, should come first from the integral experiments (IETs) analysis. As the focus will be on different and more detailed phenomena, the analysis may initiate requirements for new SETs or SETs with different and additional measurements. The other method for identifying individual phenomena could be the use of PIRT based on the accumulated knowledge on plant transients.

CFD code has in single phase flow a long tradition of simple test cases on which the models are developed and assessed. These tests cases should be part of the analytical experiments (AETs) package. As example of such programme we can note the backward facing step, the pipe expansion, the 2D rib, the driven cavity, the natural convection, impinging jet, nozzle flow. … In two phase CFD, one can imagine and it is certainly highly desirable that similar test cases would be defined and performed.

The application of the strategy established in France in the late 70's for system thermalhydraulic codes and which leads to the four levels of experiments, AETs, SETs, components, IETs is in fact very similar to the recommendations which have been elaborated for CFD in 1998 by the American Institute of Aeronautics and Astronautics (AIAA) [5]. It has also many common features with the analysis of CFD validation realized in 2002 in [6]. The AIAA guide recommended to use for validation a building block approach with distinct tiers, four for example going from the complete system to the subsystem cases, the benchmark cases and the unit problems. Although this validation hierarchy in AIAA is claimed [6] to apply more to an engineering perspective as opposed to a scientific or research perspective, the hierarchy construction is analogous to what was done in NRS, that is uncoupling from one tier to the next and frequently on the basis of physical process. In [6] complete system and subsystem tier are explained to be linked to hardware segregation, but with close relationship "in terms of physical process or functionality". The benchmark tier is said to "represent the transition from a hardware focus in the two top tiers to a physics based focus in the bottom tiers of the hierarchy". For unit problems "one should identify simple geometry experiments that have a single element of physical process complexity". Similarities of benchmark tier and unit problems with SETs and AETs strategy where individual phenomena are simulated; are evident. At the top, IETs are simulation of a system (the reactor) or of a sub system (part of the reactor) but with oriented similitude criteria which makes their response as representative as possible of the system but not identical as considered in [5].

It appears from the preceding discussion and from the experience gained in NRS thermalhydraulics in the last 25 years that experimental validation programme on CFD code (single and two phase) should follow a tier hierarchy leading to the well-known structure AETs, SETs, Components, IETs. This CFD code validation programme will have certainly to include new experiments at least because measurements should be adapted for providing the necessary information for CFD code assessment and because the physical objectives are indeed sometimes different because much more detailed.

CFD code development and assessment process

The role of SETs and IETs in the CFD code assessment should be similar than for system thermal hydraulic codes. Assessment on SETs will provide the capabilities of the CFD code to predict each physical phenomenon separately. Assessment on IETs will provide the capabilities of the CFD code to predict phenomena all together and in particular their interaction and their coupling. As IETs cannot be completely representative of the plant, transposition is also an open question for CFD codes and as previously this is obviously a key question that must not be forgotten. An adequate assessment method has certainly to be defined and applied in order to improve the presumption that the quality of the code prediction of IETs in distorted conditions can be extrapolated to the plant with sufficient confidence. In [4], when the application domain is not covered by the validation domain, the transposition (called inference in [4] from the validation to the application domain is claimed

> "(to) be made using both physics based models and statistical methods. The need to perform this extrapolation reinforces (the) need for models to be judged on the basis of achieving the right answers for the right reasons in the validation regime. Model calibration, which employs explicit tuning or updating of model parameters to achieve improved agreement with existing validation experiments, does not fully assess uncertainty in the predictive use of the model."

This recommendation is fully consistent with the conclusions that were drawn in system thermalhydraulics. The need to put the models and their qualification ("right answers for the right reasons") in the centre of the transposition process ("inference") in order to improve the presumption of the code extrapolation capabilities withstand for the CFD codes in the same way it was recognized for the system thermalhydraulic codes. Moreover, as explained in [4], calibration of models, tuning or updating which are parts of the code development could not contribute fully to the validation, and there is clearly a need to build an adequate strategy defining a proper relation between development and assessment. This relation should accommodate some independency between development and validation in order that modifications performed in the development have only an objective of improving the physics and not of improving the agreement with validation experiments and namely IETs by an artificial tuning. This independency has been tried to be achieved in the French strategy on thermalhydraulic system codes by attributing a different role to SETs and to IETs and by formalizing the development steps with frozen code versions as described in § 4.1. Iterations between development and assessment were defined where the codes were assessed on IETs, physical models worked out on SETs and not tuned on the IETs leading to new code version which was again checked on the IETs. At the end of the iteration, when satisfying agreement was obtained on the IETs, the agreement could be considered as the result of the quality of the physical model and there was therefore some argued presumption that the code will have some capability to extrapolate to the plant. A similar strategy should be defined for CFD codes.

In this strategy, the point, which remains out of control in the transposition, is the effect of the simplifying assumptions of the models which introduces shortcomings in the numerical prediction and which makes the transposition more or less credible. The more sophisticated is the model, the less numerous are these assumptions. In the examples developed in § 2, the first models used, employed very crude approximations (lumped parameters, correlation type prediction,…) and their main difficulty was that their transposition capability was highly questionable. Thermalhydraulic system codes have represented a large progress and CFD codes represent a further step in this progress. As the models in CFD simulate the elementary mechanisms determining the behavior of the fluid, one can expect that the transposition capability will be improved but it has still to be demonstrated. For developing the elementary mechanisms models, analytical experiments (AETs) play a key role and the development /assessment strategy for CFD could be probably built giving a more important and specific role to those analytical experiments (AETs) in the same way we did with the SETs for the thermalhydraulic system codes. Care should be taken in order to ensure the "kind of independency needed" for development and assessment and to avoid the limitations that we encountered with the thermalhydraulic system codes. Series of analytical experiments are available for single phase flow, it is clear that the situation is different in two phase flow and it would be certainly desirable to start a programme of two phase flow analytical experiments which could support the two phase CFD code development. This programme could be significant but it would be the main supporting argument for the transposition.

5. CONCLUSIONS

The objective of this paper was to review safety issues concerning nuclear power plant and to analyze the contribution of CFD to these issues. Three examples of safety cases where CFD analysis is necessary have first been described. Those examples are in vessel mixing, Pressurized Thermal Shock (PTS) and containment hydrogen distribution. They show that simplified modelling had been often chosen as a first step for giving answers to Nuclear Reactor Safety (NRS) issues. It appears also that the simplified modelling was generally extensively assessed on experiments but that several limitations make their prediction on plants questionable. As the experiments on which these codes are assessed cannot be fully representative of the plant, the transposition that the code has to make from the experiments to the plant is questionable, a good fit on an experiment being not a guarantee of a good prediction on the plant. Moreover, the effect of the simplifying assumptions of the models cannot be controlled in the transposition process, which may completely distort the plant response prediction. As a consequence, the way in NRS to reach practical answers with simplified modelling is to use a conservative approach. Conservatisms are taken in order to cover all the unknowns embedded in the simplifications and so that sufficient safety margins will be ensured. The problem raised by conservatisms is that it is quite difficult to determine whether the conservatisms are sufficient and what they become in the transposition process.

Transposition appears then as the key problem for answering NRS issues. To improve the transposition capability, orientations towards more physical models have to be taken. The expectation is to obtain or to approach the true physical system behavior. It is also anticipated thanks to the physics embedded in the models that the effect of changes in scale and in conditions from experiments to the plant can be predicted or better approximated. CFD code approach enters in this orientation towards more physical and more detailed tools. This type of modelling is required in several situations in single phase and two phase flows in particular when multidimensional effects are occurring in the plant.

Use of those codes for NRS application purposes requires that the applicability of the codes be demonstrated for the expected applications. The validation process intends to provide this demonstration. A specific strategy based on a combined experimental and analytical approach has to be used for handling the question of the transposition in the validation process. This strategy includes three steps: a) experiments are performed to simulate as closely as possible in a global or partial way the plant transients, b) codes are developed and assessed on the experiments, c) the assessed codes are applied as basic tool for the transposition to the plant.

The definition of experiments covering physically the plant transient lead to four categories of experiments which have been usually denominated in thermalhydraulics, separate effect tests, analytical tests, component and integral experiment tests. Assessment of the codes on these categories will provide different information: Assessment on separate effect and analytical tests will provide the capabilities of the code to predict individual phenomena whereas assessment on integral experiment tests will provide the capabilities of the code to predict phenomena all together and consequently their interaction and their coupling. But as integral tests cannot be completely representative of the plant the transposition problem remains open. Improving the capability presumption for transposition relies in fact on the quality of the physical models. A proper relation between development and assessment has consequently to be defined. This relation should accommodate some independency between development and validation in order that modifications performed in the development have only an objective of improving the physics and not of improving the agreement with integral experiments by an artificial tuning. When satisfying agreement is obtained on integral experiments, this agreement can then be considered as the result of the quality of the physical model and one can therefore presume that the code will have some capability to extrapolate to the plant. The only point, which remains out of control in the transposition process, is the effect of the simplifying assumptions. For CFD codes these assumptions are reduced at their maximum and one can expect improved transposition capability compared to other system thermalhydraulic codes.

In the code development and assessment process, experiments play a key role. It is clear that packages of separate effect tests, analytical tests, component and integral experiment tests have to be defined in support of CFD codes. Some experiments already exist in particular in single phase flow but others have certainly to be set up in particular in two phase flows. CFD codes belong to the category of the highly mechanistic codes based on microscopic constitutive laws that are developed in several engineering domain. The resulting numerical simulations are quite sophisticated and many people think that those codes "describing reality" can save experimental programmes that will not be anymore necessary. This question is also often raised by managers who ask whether such codes could substitute experiments. On a physicist point of view this is certainly a wrong and dangerous statement, and the important validation needs of the CFD codes is a good example of the necessary link with the experiment. The type of validation experiments for those highly mechanistic codes may be shifted compared to the previous codes (more analytical than global) but all kinds of experiments certainly remain indispensable. In NRS, the transposition question which people are often not sufficiently aware when practical problems are solved, reinforces clearly this experimental need for CFD codes.

Finally, we shall say some words on the uncertainty question. As explained in [1], the vocation of CFD codes in NRS is certainly to be used for best estimate calculations with uncertainty evaluation. Different sources of uncertainties are generally distinguished which can be handled by different methods. The most crucial category of uncertainty is certainly the epistemic uncertainties. Their evaluation should certainly be strongly linked to the assessment and their relation with the transposition problem is certainly a point that needs clarification. If large assessment programmes had to be launched (for example for two phase CFD), it would be wise to consider simultaneously the epistemic uncertainty question as it will help in clarifying several other questions that are quite general and that have not been discussed here such validation metrics, etc…. Those questions will help in optimizing the experimental and the associated assessment programmes.

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