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Perspectives on CFD analysis in nuclear reactor regulation

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ABSTRACT

The U.S. Nuclear Regulatory Commission is tasked with ensuring that the commercial use of nuclear materials in the United States is safe. This includes the review and evaluation of submitted analyses that support the safety justification for specific reactor-system components or scenarios. Typically these analyses involve the use of codes that have a proven history of validation and acceptance for the specific application of interest. The use of computational fluid dynamics (CFD) has not been as widespread in regulatory activities and the experience level with acceptance is more limited. The ever-increasing capacity of computers, along with the growing number of capable analysts, ensures us that CFD applications will continue to grow in usage for nuclear safety analysis. The challenge ahead is to ensure that these tools are properly validated and applied in order to build up the necessary evidence for more common acceptance in regulatory processes. The challenges include a continuation of the development and maintenance of best-practice guidance, development of problem-specific CFD-grade benchmark studies, the application of verification and validation techniques, and the development of practical treatments for uncertainties and scaling. Through these efforts, it is anticipated that CFD methods will continue to gain acceptance for use in nuclear reactor safety applications.

1. Introduction

The U.S. Nuclear Regulatory Commission (NRC), like all nuclear safety regulators worldwide, is tasked with regulating its nation's civilian use of radioactive material to protect public health and safety. These principles are laid out in the NRC's mission statement (Nuclear Regulatory Commission (NRC), 2014) as well as in international guidelines such as the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) report "The Characteristics of an Effective Nuclear Regulator" (NEA, 2014). The regulatory mission includes the review and evaluation of licensee-submitted analyses that support the safety justification for specific reactor-system components or scenarios. In many cases, these analyses involve codes that have been approved for the specific application of interest after the corresponding approach has developed a proven history of validation and acceptance in the regulatory environment. The application of CFD in regulatory activities is not yet common but the number of applications is growing. The application of CFD is common practice in many industries and its use is growing in the nuclear industry as well. The increasing capacity of modern computers, the growing number of capable analysts, and the expected use of CFD for the design of new systems ensures us that the use of CFD will continue to expand into regulatory applications.

The NRC recognizes the growth of CFD methods that support nuclear-reactor safety analyses and is leveraging resources to further develop and maintain capabilities in this area. This includes developing knowledge and expertise through cooperative initiatives, benchmark exercises, specific test programs, targeted CFD model developments, verification and validation initiatives, and the support for and development of CFD best-practice guidelines. In addition, the NRC uses CFD, where appropriate, to support the resolution of safety issues and for confirmatory analyses supporting licensing decisions. The regulatory mission of protecting public health and safety, however, requires a regulator to look critically at submitted analyses. The positive contributions from CFD must be considered along with the potential limitations and uncertainty.

The submission of CFD applications to the NRC ranges from licensing-basis calculations, such as those supporting the thermal analysis of spent fuel storage and transportation systems, to background studies that provide support for system analysis code predictions or some specific safety feature. In the case of fuel storage and transportation systems, where regulatory acceptance of CFD methods is most common, the NRC has developed years of experience which has resulted in application-specific best-practice guidelines (Zigh and Solis, 2013). These guidelines help facilitate reviews and set expectations for the development of high-quality CFD simulations. This is a prime example of an effective use of CFD

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in the regulatory environment but this situation did not develop overnight. There has been a focused effort for years to develop appropriate test data and benchmark studies to support the validation of CFD modeling approaches. In this particular example, the industry has maintained an interest in developing and submitting these types of simulations for licensing fuel storage and transportation systems and the NRC has developed the required experience to ensure that these models can be reviewed in an efficient manner. The applicability of the CFD tools and the potential uncertainties are well understood and there is a growing history of regulatory acceptance of high quality models for this application. This is an example of what is possible when a sustained effort is made over a number of years to develop and validate the approach.

For some potential CFD applications in the nuclear safety area, the situation is not so well developed. The lack of full-scale CFD grade benchmark data is a major limitation. This makes it difficult to validate the models. For many problems, application specific best practice guidelines are not available. Experience must be developed over time with each new scenario. Another issue relates to the scale and complexity of some models. Reactor components can be large and many contain detailed internal structures which impact the flow field and heat transfer. These design details are expensive to model from both a time and computational resource perspective. Simplifications to geometry and modeling approaches are common in many reactor scale problems. The effectiveness of the approach can be highly dependent on the users experience and this results in a challenge for the reviewers. New and complex modeling approaches require significant regulatory reviews to build faith in the methods. These types of reviews are completed on a case-by-case basis without the benefit of application specific best practice guidance and review plans. Regulators must rely on more high level guidance which does not provide insights into the impact of the many detailed modeling choices incorporated into a complex reactor safety model. The burden is on the licensee to demonstrate that CFD predictions are completed using a valid approach and that uncertainties are properly quantified. The regulator must ask the question of whether or not the results can be trusted. Significant work is required to build confidence and ultimately acceptance for new methods used for regulatory applications.

2. A view of the state of the art

The “state of the art” typically refers to the highest level of a technique or knowledge base in a given area of study. For CFD applications, the state of the art still involves some level of “art” or creativity as suggested in the CFD textbook *Fundamentals of Computational Fluid Dynamics* (Roache, 1998). On page 1 of this book, the author suggests that “in this field, there is at least as much artistry as science.” This is difficult to understand for those not practicing CFD on a routine basis. The scientific and mathematical aspects of CFD are surely well known based on the proliferation of best-practice guidelines, the establishment of verification and validation standards, the availability of well-documented codes and models; the multitude of dedicated CFD conferences, journals, and workshops; and the large worldwide user base supported by dedicated university programs. In spite of all of these supporting structures and initiatives, artistic (or creative) approaches are still commonplace because users are faced with the practical limitations of non-universal models along with finite time, knowledge, and computer resources. These limitations are amplified when users are faced with some of the large and complex flow problems associated with nuclear reactor safety. In many scenarios facing the nuclear safety community, CFD models are routinely developed using creative approaches to facilitate practical solutions in light of the limitations noted above.

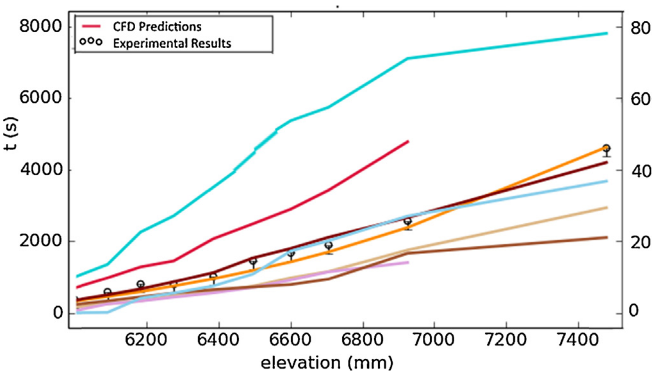

Fig. 1. Predicted helium layer erosion times compared to test data.

Benchmark studies are one way to measure the state-of-the-art for CFD methods in relation to a given application. Benchmark test programs provide the opportunity to compare predictions to test data in a carefully controlled environment where geometry and boundary conditions are well documented. Blind benchmarks, such as the recent (2013–2014) OECD/NEA sponsored containment benchmark in the Panda facility, are most enlightening since the analysts do not have access to the experimental data until after their predictions are completed. The benchmark involved testing in one of the drywell tanks from the PANDA facility. Helium was injected carefully into the top portion of the vertical cylindrical tank in order to establish a stratified helium layer. This stratified helium layer was broken down by erosion from a vertical jet from lower in the tank. The speed of this erosion process was the main attribute of the benchmark. The results were recently presented as a keynote speech at the 2014 CFD4NRS-5 workshop in Zurich, Switzerland. Fig. 1 shows one of the set of results presented for several of the participants. The plot shows the predicted times (y-axis) at which the helium concentration drops to a pre-determined level for various elevations in the tank (x-axis). The test data are illustrated by circles and the CFD predictions are shown as lines. The predicted times range from approximately 50–200% of the measured values. These results are consistent with the author’s perceptions from other blind CFD benchmark studies.

The variations in the predictions are significant but it is important to note that one might expect larger variations if a study were completed for a complex reactor safety issue where boundary and initial conditions are not so well defined and geometry simplifications may be required. This OECD benchmark problem included relatively simple geometry, known flow behavior, clearly defined boundary and initial conditions, a history of related test programs at the same scale, and a significant number of related publications. In many reactor safety problems, these supporting factors are not present. Many scenarios involve complex geometry, uncertain or complex flow behavior, uncertain boundary and initial conditions, limited or no full-scale test data, and limited related publications. Variations observed in this benchmark study, therefore, do not include all of the factors which would be included in the uncertainty associated with predictions of prototypical reactor safety scenarios. This knowledge increases the burden on licensees to demonstrate that predictions are valid and that uncertainties are quantified when submitting CFD predictions for regulatory acceptance.

Finite time and computer resources are a common issue for the CFD modeller. Modern computers continue to increase in capacity and drop in price but the nuclear-safety analyst is still routinely limited by available resources. Domains of interest can range from a single steam-generator tube or pipe junction to an entire core, fuel pool, or containment. External plant modeling examples include