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A CFD simulation process for fast reactor fuel assemblies

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ABSTRACT

A CFD modeling and simulation process for large-scale problems using an arbitrary fast reactor fuel assembly design was evaluated. Three-dimensional flow distributions of sodium for several fast reactor fuel assembly pin spacing configurations were simulated on high performance computers using commercial CFD software. This research focused on 19-pin fuel assembly "benchmark" geometry, similar in design to the Advanced Burner Test Reactor, where each pin is separated by helical wire-wrap spacers. Several two-equation turbulence models including the k–ε and SST (Menter) k–ω were evaluated. Considerable effort was taken to resolve the momentum boundary layer, so as to eliminate the need for wall functions and reduce computational uncertainty. High performance computers were required to generate the hybrid meshes needed to predict secondary flows created by the wire-wrap spacers; computational meshes ranging from 65 to 85 million elements were common. A general validation methodology was followed, including mesh refinement and comparison of numerical results with empirical correlations. Predictions for velocity, temperature, and pressure distribution are shown. The uncertainty of numerical models, importance of high fidelity experimental data, and the challenges associated with simulating and validating large production-type problems are presented.

1. Introduction

With global energy consumption expected to increase by over 50% by the year 2030, there has been an international effort to design and build advanced nuclear power plants capable of providing a safe, clean, and sustainable energy supply. Given the underlying programmatic, financial, and technical constraints of new designs, it is clear that building expensive prototypes is not practical; therefore, modeling and simulation (M&S) will be relied upon throughout the nuclear power plant life-cycle management process. Streamlined M&S processes and computing system productivity improvements will be key success factors in meeting project cost and schedule commitments, including design objectives, for international and domestic energy initiative programs.

In an effort to meet programmatic goals, recent advances in technology and the need for high fidelity computational data have resulted in research efforts focused on the integration of multi-physics phenomena and the development of new and improved numerical solvers and physical models. These contributions are expected to significantly reduce the uncertainty and increase the accuracy of M&S tools, allowing scientists and engineers to better predict physical phenomena such as critical heat flux (CHF) and reduce the uncertainty associated with hot channel factors, which in general represent the ratio of maximum to nominal values of parameters such as reactor temperature or power. Unfortunately high fidelity computational data, which implies better representation of the physical geometry and accurate resolution of physical phenomena, requires more computer memory, larger data storage, improvements in data management, faster data processing and transfer, and robust visualization tools.

However, minimal emphasis has been placed on the simulation of large production-type problems using state-of-the-art commercial software and hardware. Large-scale simulations have the potential of providing insight into the problems and challenges that can be expected upon implementing advanced M&S tools in production codes and on advanced HPC systems. Identifying and solving these problems early in the research phase minimizes the impact on project cost and schedule during the design and development phase of new generation nuclear power plants.

This paper provides an overview of the general M&S process that was followed for this study, and then expands on the verification and validation (V&V) methodology. Primarily, methodologies and preliminary results are presented. Theoretical aspects of the

Abbreviations: ABTR, Advanced Burner Test Reactor; CAD, computer aided design; CFD, computational fluid dynamics; CHF, critical heat flux; HPC, high performance computing; HTFF, heat transfer and fluid flow; M&S, modeling and simulation; SST, shear stress transport; V&V, verification and validation.

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Nomenclature

Symbols

D	pin nominal diameter
D_s	wire-wrap nominal diameter
D_ℓ	assembly flat nominal length
D_{ft}	assembly flat-to-flat nominal distance
P	pin pitch
ΔP	clearance per interior pin
g	outer ring pin-to-wrapper clearance
Δg	outer ring wire-wrap to wrapper clearance
T	magnitude of the as fabricated clearance or tolerance along the flat-to-flat direction
F	fraction of the assembly tolerance T which is distributed around the interior rods

commercial CFD software, for example numerical solvers and turbulence models, can be found in the STAR-CCM+ User Manual (CD-adapco, 2007) or the literature.

1.1. Purpose of study

The purpose of this study was to investigate and evaluate a computational fluid dynamic (CFD) M&S process, which included CAD geometry development, meshing, simulation, and post-processing of results, for large problems using an arbitrary fuel assembly design as a benchmark problem. Preliminary three-dimensional flow distributions of sodium for several fast reactor fuel assembly pin spacing configurations were simulated using commercial CFD software and high performance computers (HPCs). This study focused on a 19-pin fuel assembly, similar in design to the Advanced Burner Test Reactor (ABTR), with wire-wrap spacers. Assembly nomenclature, consistent with that presented by Todreas and Kazimi (2001), is adhered to. Several geometric models, with different inner pin spacing and helical pitch, were developed for the study. Three, two-equation turbulence models including the k–ε and SST (Menter) k–ω were evaluated. Considerable effort was taken to resolve the momentum boundary layer, so as to eliminate the need for wall functions. High performance computers were required to generate the hybrid meshes needed to predict secondary flows created by the helical wire-wrap spacers; computational meshes ranging from 65 to 85 million elements were common. A general validation methodology, which included examining iterative convergence, consistency, spatial convergence, temporal convergence, comparison of CFD results with experimental data, and examining model uncertainties was followed (NPARC Alliance, 2007). Additionally, a speedup curve was developed to help assess computational productivity. Predictions for velocity, temperature, and pressure distribution are shown. The uncertainty of numerical models, importance of high fidelity experimental data, HPC productivity, and the challenges associated with simulating and validating large production-type problems are discussed.

2. Modeling and simulation

The M&S process was comprised of a four phases which included creating a solid model using commercial CAD software, generating a computational mesh and running the simulation on high performance computers (HPCs) using commercial CFD software, and conducting rudimentary validation studies using dated empirical correlations published in the literature. Lessons learned from scoping studies of a single-pin and a three-pin assembly were incorporated into the analysis.

Commercial software was used for this study because of its robustness, functionality, and ability to provide quick-turnaround solutions for a wide range of problems. The ability to import a wide range of CAD files, select different meshing models, numerical solver and turbulence model selection, and post-processing capabilities provides the CFD practitioner with a versatile toolset for modeling and simulation. For example, the geometric complexities created by modeling the wire-wrap spacers made the use of less sophisticated solid modeling techniques impractical. The CAD software provided the capability to automate the model allowing fuel assembly geometric design changes to be made quickly. This was important when evaluating modeling tradeoffs because several geometric design changes were required before a computational mesh of sufficient quality was obtained. Finally having quick access to several turbulence models was advantageous, especially when conducting sensitivity analysis studies.

2.1. CAD model

A computer aided design (CAD) solid model of a 19-pin fuel assembly was created using SolidWorks, commercial software (SolidWorks, 2008). The software was automated with geometric equations and terminology consistent with that presented by Todreas and Kazimi (Todreas and Kazimi, 2001). For example, geometric parameters and terminology such as "clearance per interior pin – Δp", "flat-to-flat tolerance – T", and "the fraction of assembly tolerance distributed within the rods – F" were adhered to. Several geometric models were developed for this study. Models M(1) thru M(3) were developed for the preliminary isothermal hydrodynamic simulation which included a turbulence sensitivity analysis study, and model M(4) was developed for the heat transfer and fluid flow (HTFF) analysis. Additionally, models A, B, and C were developed for the wire-wrap sensitivity analysis study.

Models M(1) thru M(3) were 20 cm in length with a helical pitch of 20.3 cm, and model M(4) was 20.3 cm in length with a helical pitch of 20.3 cm. Table 1 presents the geometric details of each model, including the ABTR geometry; a description of the geometry is shown in Fig. 1. The fuelpin solid model and computational volume are shown in Figs. 2 and 3. The rotation direction of the spacer wire is clockwise when viewed from the rod-bundle outlet, Fig. 3. Although the fuelpin solid geometry could have been modeled together with the computational fluid volume, for example a conjugate heat transfer analysis, the number of mesh elements would have been prohibitive for preliminary scoping studies.

Table 1
Geometric model parameters.

Model	Pins	D	D_s	P/D	P	ΔP	Δg	D_{ft}	D_ℓ	Length	T	F
ABTR	217	0.800	0.103	1.130	0.904	0.001	0.033	13.598	–	260	0.0797	0.174
M(1)	19	0.800	0.103	1.169	0.936	0.039	0.032	4.299	2.482	20.0	0.2001	0.675
M(2)	19	0.800	0.103	1.149	0.919	0.023	0.016	4.210	2.431	20.0	0.1113	0.708
M(3)	19	0.800	0.103	1.135	0.908	0.012	0.005	4.148	2.395	20.0	0.0498	0.799
M(4)	19	0.800	0.103	1.127	0.902	0.005	0.005	4.126	2.382	20.3	0.0273	0.634

Notes: (1) All dimensions in centimeters; (2) model geometry includes a pin-to-wire-wrap overlap of 0.0065 cm.