Thermal Stratification Modeling and Analysis for Sodium Fast Reactor Technology

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INTRODUCTION

The pool-type sodium fast reactor (SFR) is a prominent design concept for generation IV nuclear reactors. In order to advance the scientific framework used to analyze SFR technology significant work must be done to improve existing computational models used for reactor analysis. Specifically, there has been a demonstrated need for the advancement of computational models that predict thermal stratification behavior during reactor transients. Thermal stratification in the upper plenum of a pool type reactor, which may occur during reactor transients, can cause cyclic stress on the reactor vessel and potentially lead to mechanical failure. A reactor transient known to lead to thermal stratification in the upper plenum is a reactor trip (Fig. 1)[1].

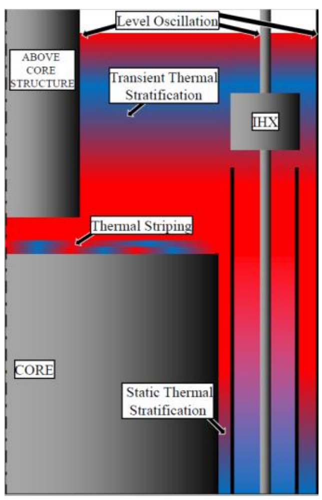

Figure 1: A schematic of thermal stratification that can exist in the reactor pool in the event of a reactor trip (Blue represents colder sodium and red represents hotter sodium).[1]

During a reactor trip one of the postulated events that must be considered is a loss of flow in the reactors primary coolant system. This loss of flow is considered either a protected or unprotected loss of flow (PLOF and ULOF). PLOF implies that the reactor successfully scrams. In the PLOF scenario a reactors core temperature is effectively lowered when the control rods are inserted into the core. This injects colder fluid from the reactor core into the hotter reactor pool potentially causing stratification. In a ULOF scenario the reactor does not successfully scram and thus the core temperature immediately begins to rise thus injecting hotter fluid into a colder pool. The mixing of two different temperature fluids at the interface of the core exit and the reactor pool is known to cause thermal stratification throughout the reactor pool (Fig. 1).

A facility has been designed and developed at the University of Wisconsin – Madison to study thermal stratification phenomena in large pools of sodium both experimentally and computationally. This research is specific to phenomena discovered in the hot pools of pool-type sodium fast reactor (SFR) designs. While there have been attempts to model thermal stratification behavior in some SFR designs, further experimentation is still required to create more intricate and reliable models. SFR designs like Argonne National Laboratory's (ANL) Advanced Burner Test Reactor (ABTR) have been analyzed with a system code for the occurrence of stratification[2]. However, this model has several shortcomings. In order to improve upon this model so that it may be used to vet future reactor designs it must also be coupled with experimental data and computational fluid dynamic (CFD) code. Coupling the computational models with the experimental data will help to develop an efficient base model for predicting thermal stratification.

Project Objectives

The primary goals of this project are to examine thermal stratification behavior in a pool type geometry (UW-Madison group), use data obtained from the stratification experiment to inform computational fluid dynamic codes (MIT group) and system codes (VCU group), and to train graduate researchers on techniques and practices used to research sodium fast reactor technology. Key guidance on all three of these endeavors is being provided through scientists at Argonne National Laboratory.

The initial stage of the project focused on the design and development of the thermal stratification testing facility. Initial design concepts were first verified by CFD codes using an unsteady Reynolds-averaged Navier-Stokes (URANS) turbulence modeling approach. While not ultimately indicative of the exact behavior that might exist in the proposed designs, this modeling approach allowed for a good approximation of thermal stratification behavior in each design. A final design was selected and construction for the experimental facility has been completed. Initial data acquisition and comparison will be completed by the fall of 2018.

In parallel with the efforts made by the CFD and experimental groups, the system codes group has made significant progress in developing a thorough literature review regarding past studies on thermal stratification. The literature review identified gaps in past thermal stratification research to be addressed by this project. Furthermore, efforts have been made to investigate machine learning algorithms that can be used to advance reduced order modeling approximations used in system code stratification analysis.

Experimental Design

The Thermal Stratification Testing Facility (TSTF) sodium loop was completed in the spring of 2018. The TSTF is designed to scale to the geometry of the ABTR and will use sodium as the primary working fluid[1]. The experiment was designed on the following dimensionless number ratio criteria between the designed experiment and the ABTR: similitude in the Richardson number, low ratio of the Peclet number, and a low ratio of the Reynolds number[1]. Analysis of these dimensionless numbers led to the test section design shown in Figure 1.

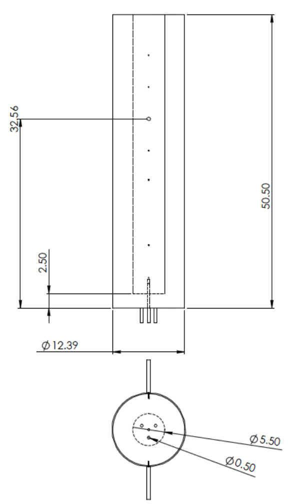

Fig. 1: The design of the test section for the TSTF.

Computational Fluid Dynamics

Computational fluid dynamics (CFD) can be used in the nuclear industry to inform the early development, design, analysis, and optimization of systems and components. In this project, CFD is adopted initially as an experimental design tool. This tool allows for optimization and scaling of the experimental facilities, positioning of the measurement systems, and the ability to identify potential issues related to three dimensional flow configurations. Conversely, the availability of the transient three-dimensional temperature experimental measurements in a sodium pool will support rigorous validation of the momentum and heat flux closures in the CFD modeling. This information is expected to support the formulation of best practices for thermal stratification analysis in liquid metal cooled type reactors, particularly SFRs.

While direct numerical simulation (DNS) and large eddy simulation (LES) methods are computationally restrictive for typical high-Reynolds-number reactor flow applications, considerable work has been performed based on the steady and URANS turbulence modeling approaches. However, the classic URANS models suffer considerable limitations in the description of flow fields. Some improvement can be provided adopting nonlinear eddy viscosity models (NLEVM). In these models the cubic formulation by Baglietto and Ninokata[3,4] is adopted for this preliminary CFD simulation.

Later work will leverage the new experimental data and focus on quantifying the significance of large unsteady structures on the flow distribution. A recently developed structure-based (STRUCT) hybrid URANS/LES turbulence approach[4,5] will be adopted to address this challenge. The STRUCT method aims at accurately predicting thermal stratification. Hybrid models fill the gap between the URANS and LES models, and will provide increased flow resolution while limiting the computational cost. The newly proposed STRUCT model originates from overcoming the URANS limitations in the simulation of industrial unsteady flows, while maintaining robustness and feasible grid requirements for large-scale applications. The soundness of the STRUCT approach has been demonstrated through its application to a variety of flow cases, including configurations that had not been addressed successfully by other hybrid models.

System Code Introduction

There are several methods that can be used for modeling thermal stratification, including 0D, 1D, and 3D approaches. While 3D approaches that couple CFD modelling with systems codes can provide an enormous amount of information, it is computationally expensive and not practical for design and licensing purposes. Currently most system codes, including SAS4A/SASSYS-1 employ a 0D approach but result in approximate results at best. Several 1D approaches have been examined, but have proven difficult to use in transient situations.

The current stratified volume model in SAS4A/SASSYS-1 will be compared to the experimental results from the TSTF. Once this is done, the experimental data will be used to develop an improved 0D stratified volume model. Depending on these results, a 1D solution will also be explored. An issue that may be encountered for a 1D model is the ability to handle a transient situation such as PLOF or ULOF – both of which cases are examined experimentally through this project.

RESULTS

Experimental Data

The thermal stratification facility has been constructed as of the spring of 2018 (Fig. 2). The total working volume of sodium in the experiment is 100 gallons. The facility has access to 250 gallons of reactor grade sodium.

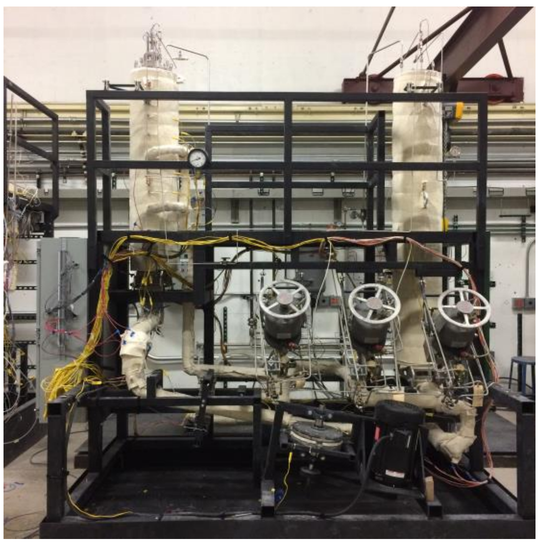

Figure 2: Thermal Stratification Testing Facility as of May 2018.

Experimental data will be collected in the experimental test section with high accuracy temperature measurement devices. Thermocouples will obtain measurements at several points in space inside of the large volume while optical fiber temperature sensors will obtain distributed temperature readings axially inside of the test section. This understanding of temperature will allow for a visualization of the stratification that will occur inside of the test vessel. Optical fiber deployment techniques have been thoroughly researched and are suitable for this practice[6]. Sodium will be moved throughout the facility using a moving magnet pump (MMP) and the velocity of the incoming sodium will be measured via an electromagnetic flow meter[7,8].

The first series of tests to be conducted in the experimental facility will analyze the PLOF scenario (cold sodium into a hot sodium pool). This data will serve as a bench mark for analyzing consequent experimental campaigns. Based on predictions made by the initial CFD simulations it is expected to see stratification formation within the first 100 seconds of an experiment when the flow rate into the experimental vessel is 5 [gpm]. Once the testing campaign successfully commences the experimental facility can be altered in the following ways: UIS diameter, UIS height above the core, UIS design, fiber measurement location, number of inlets (1, 2 , or 3), Outlet height (1/3 or 2/3 of the total height), temperature difference (cold into hot or hot into cold), temperature range (200-300 [C]), and sodium flow rate (5-20 [gpm]).

Initial CFD Results for the TSTF

A preliminary CFD simulation for the first thermal stratification test is conducted using the commercial finite-volume code STAR-CCM+ Version 12.02 in combination with the cubic *k-ε* model[3,4]. Fig. 3 shows the computational mesh for the TSTF test section. In total 4.59 million cells are used to represent the geometry.

For the boundary conditions, three pool inlets are set as velocity inlet with constant velocity of 0.830196 m/s and inlet temperature of 200 C; the two pool outlets are set as pressure outlet; all other parts and pool surfaces are set as adiabatic walls. Initial conditions model a uniform temperature of 250 C across the entire domain. The time step is chosen to yield a maximum Courant number of 1. Development of thermal stratification is expected as the cold sodium starts to be injected into hot sodium at t = 0 s. Figure 5 shows the evolution of the temperature distribution in the y-z plane. A stratified temperature gradient is clearly observed. After 250 s, the temperature gradient above the outlets is controlled by thermal conduction and develops slowly.

Once the experimental data becomes available, a more detailed mesh study will be conducted, and the newly proposed STRUCT model will further be assessed on this case.

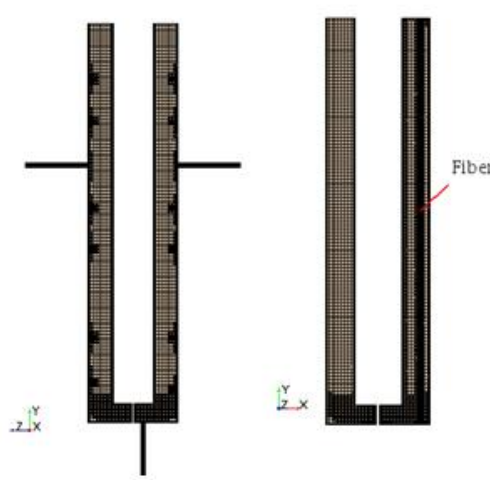

Figure 3: Computational mesh in the y-z plane and x-y plane.

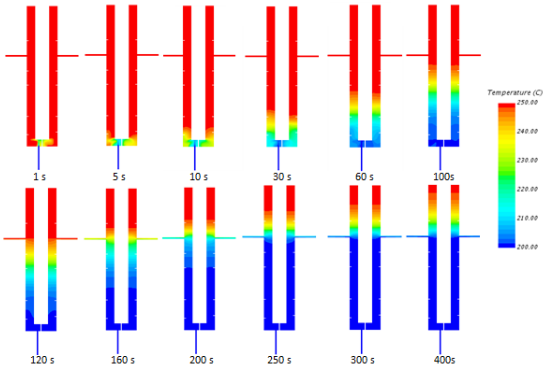

Figure 4: Evolution of temperature distibution in y-z plane.

Future Plans for System Code Development

The ultimate objective of this project is to develop 0D or 1D enhanced models for thermal stratification that can be successfully implemented in currently used systems codes such as SAS4A/SASSYS-1 and SAM. The development of these models will be based on the experimental data and the CFD simulations performed by UW and MIT respectively. .

CONCLUSION

The thermal stratification testing facility will be used to obtain high fidelity data and computational fluid dynamic simulations that will be used to inform the development of enhanced thermal stratification models for system codes. These revised models will make system codes capable of better predict the behavior of sodium cooled reactors during complex transients. Having more trust in the capability of computer generated models to produce accurate results is vastly important to informing a nuclear reactor design.

ACKNOWLEDGMENTS

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