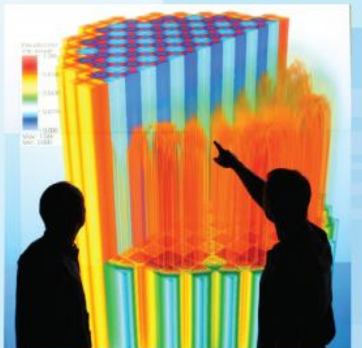
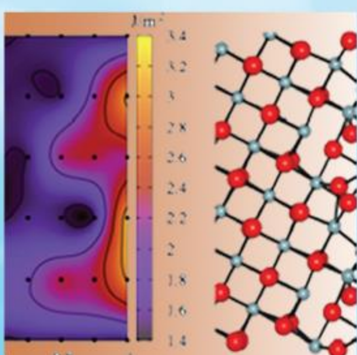
CASL-U-2013-0198-000

Power uprates and plant life extension

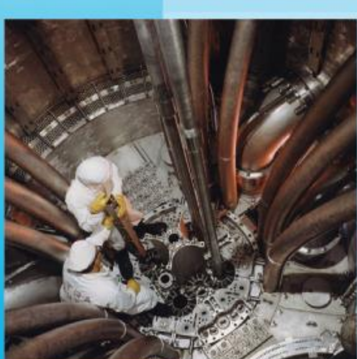


Engineering design and analysis

Science-enabling high performance computing



Fundamental science



Plant operational data

CASL
Consortium for Advanced Simulation of LWRs

L3:THM.CFD.P7.02
Hydra-TH Milestone Report

Yidong Xia, Hong Luo,
Jozsef Bakosi, Mark Christon,
Lori Pritchett-Sheats
NCSU, LANL

September 30, 2013

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Hydra-TH Milestone Report (L3:THM.CFD.P7.02)

Yidong Xia and Hong Luo
Computational Fluid Dynamics Laboratory
Department of Mechanical and Aerospace Engineering
North Carolina State University
Engineering Bldg 3, Campus Box 7910
Raleigh, NC 27695-7910

Jozsef Bakosi, Mark A. Christon and Lori Pritchett-Sheats
Computational Physics and Methods, CCS-2
Los Alamos National Laboratory
Box 1663, MS D413
Los Alamos, NM 87545

1 Executive Summary

This report describes the work carried out for completion of the Thermal Hydraulics Methods (THM) Milestone L3:THM.CFD.P7.02 for the Consortium for Advanced Simulation of Light Water Reactors (CASL). The main objective of the research effort in this milestone is to assess, verify, and validate the Hydra-TH code for its ability to compute single-phase turbulent flows in a nuclear reactor. Hydra-TH has been used to compute a variety of flow problems which vary in complexity from laminar to turbulent flows. Extensive testing of Hydra-TH is conducted against a number of available benchmark test cases and test cases of interest to CASL, e.g., Poiseuille flow, Blasius boundary layer, lid-driven cavity, and Taylor–Green vortex. The numerical experiments are conducted using both the well-established and state-of-the-art turbulence models, ranging from traditional Reynolds-averaged Navier-Stokes (RANS) to large-eddy simulation (LES). The following models implemented in Hydra-TH are used in the test:

- RANS models
  - Spalart Allmaras model

CASL-U-2013-0198-000

- Re-normalized group (RNG) k-ε model

- LES models
  - MILES or ILES: This family of models is obtained using a monotonicity preserving advection treatment (MILES) and is also referred to as implicit LES (ILES).
  - Smagorinsky model
  - Wall-adapted large eddy (WALE) model

The solution strategies that are used for time integration include the semi-implicit P2 projection algorithm (termed as SI-P2) and the fully-implicit Picard-iteration based algorithm (termed as FI-P2), when appropriate. The numerical solutions are compared with the available experimental data and the reference solutions in the literature. In completion, the input ExodusII format mesh files and control files are integrated in the Hydra-TH repository. Each test case is well documented and made available for Hydra-TH V&V document.

2 Milestone Accomplishments

2.1 Hydra-TH V&V Benchmark Problems

Verification testing is part of Hydra software control process and ensures that Hydra-TH is solving problems of interests to the CASL project and meeting design requirement. It is one component of a larger testing infrastructure. This work identifies verification problems and the Hydra-TH solutions to those problems. We anticipate more test problems to be added to the suite of verification and validation for flow simulation, as the Hydra-TH code will change over time.

The tests are organized by methods and physics to enable a quick survey of code capabilities. Each test has a section in the Hydra-TH V&V document, with sub-sections describing why the test case is included as a verification test (Problem Description), the set up of the test case (Problem Setup).

2.2 Poisueille Flow

The objective of of the test case in this numerical experiment is to verify if Hydra-TH can achieve a formal order of the convergence rate for incompressible laminar flows. The test problem chosen in this case is the steady Poisueille flow, which represents an exact solution to the full system of two-dimensional incompressible Navier-Stokes equations for a laminar flow in a channel. A grid convergence study is performed on a series of three successively refined hexahedral grids. The numerical results obtained are in good agreement with the analytical solution. Also, grid convergence analysis indicates that Hydra-TH is able to achieve the designed second-order of accuracy for solving the incompressible Navier-Stokes equations. The details of this work have been documented in §2.1 of the Hydra-TH V&V document [1].

2.3 Flow Past A Flat Plate

The laminar boundary layer over an adiabatic flat plate at a Reynolds number of $Re = 100{,}000$ based on the free-stream velocity and the length of the flat plate is considered in this test case. This problem is chosen to illustrate the accuracy of the Hydra-TH solution methods for the discretization of the viscous and heat fluxes in the incompressible Navier-Stokes equations, as the classical Blasius solution can be used to measure the accuracy of the numerical solution. A grid sensitivity study is performed on a series of three hexahedral grids of the same number of cells, with the same distribution of the grid points in the x-direction, but a different distribution of grid points in the y-direction. The numerical results obtained are in good agreement with the analytical skin friction coefficient distribution, and x- and y- velocity profiles. Hydra-TH is verified to demonstrate a consistent performance with high accuracy of solution for the discretization of the viscous and heat fluxes for solving the incompressible Navier-Stokes equations. The details of this work have been documented in §2.4 of the Hydra-TH V&V document.

2.4 Turbulent Channel Flow

The test case chosen in this numerical experiment is the well-known and well-documented turbulent channel flow at a friction Reynolds number of $Re_\tau = 590$. Both the Spalart-Allmaras one-equation model and the RNG k-ε two equation model with a wall function are used in the numerical experiments.

A grid convergence study is performed on a series of three successively refined hexahedral grids. The numerical results obtained by the Spalart-Allmaras one-equation model are in good agreement with the referenced DNS results. The solutions obtained by the RNG k-ε model also agree well with the DNS data. The details of this work have been documented in §2.5 of the Hydra-TH V&V document.

2.5 Large-Eddy Simulation of a Lid-Driven Cavity Flow

The test case chosen in this numerical experiment is the large-eddy simulation of a lid-driven cavity flow at a Reynolds number of $Re = 10,000$. The ILES, WALE and Smagorinsky models are used respectively in the numerical experiments. A grid convergence study is performed on a series of three successively refined hexahedral grids. The numerical results obtained by the ILES and WALE models are in good agreement with the referenced experimental data. The solutions obtained by the Smagorinsky model also agree well with the experimental data. The details of this work have been documented in §3.1 of the Hydra-TH V&V document.

2.6 Inviscid Channel Flow with Oscillating Velocity Inlet Boundary

An unsteady inviscid flow through a channel with inlet velocity at the left boundary varying in time is simulated in this test case. The main objective is to initially assess and validate the temporal discretization of Hydra-TH with time-accurate flow problems. Two solution strategies used in the test case. The first one, which serves as the baseline solution method, is the semi-implicit projection method and denoted as SI-P2. The second one, which is still under preliminary test and thus not yet formally introduced in the Hydra-TH Theory Manual [2], is the fully-implicit Picard iterative method and denoted as FI-P2. The order of accuracy for temporal convergence of the SI-P2 and FI-P2 methods is assessed. Numerical results show that the pressure term is second-order accurate in time for both the SI-P2 and FI-P2 methods, and the Lagrange multiplier is third-order accurate in time.

2.7 Taylor–Green Vortex

The Taylor–Green vortex problem is carried out in this test case in order to assess and validate the space-time accuracy of Hydra-TH with time-accurate flow problems. The Taylor–Green vortex is an unsteady flow of a decaying vortex, which has an exact closed form solution of the incompressible Navier–Stokes equations. The space-time dependent Dirichlet boundary conditions are prescribed at the domain boundaries. The solution strategies that are used for time integration include the semi-implicit P2 projection algorithm (termed as SI-P2) and the fully-implicit Picard-iteration based algorithm (termed as FI-P2). The order of accuracy for spatial discretization of velocity and pressure were assessed on a series of successively refined hexahedral grids, with the time-step values small enough to allow focusing on spatial discretization errors. The accuracy of temporal convergence of velocity and pressure were then assessed using a series of successively divided time-step values, with the grid resolution small enough to allow focusing on temporal discretization errors. The measured spatial convergence rates demonstrated that the SI-P2 and FI-P2 solution strategies achieved the second-order accuracy of velocity and pressure in space. The measured temporal convergence rates for velocity, pressure and Lagrange multiplier indicate that SI-P2 and FI-P2 achieved the second-order accuracy of velocity and Lagrange multiplier in time, while pressure remains first-order accurate with either methods. The details of this work have been documented in §3.1 of the Hydra-TH V&V document.

3 Summary

A series of seven Hydra-TH V&V test problems have been defined and carried out by Hydra-TH Milestone (L3:THM.CFD.P7.02). Future efforts will be the continuation of Hydra-TH varification and validation on more benchmark problems, which might include more complex flow environment and multi-phase flow problems.

ACKNOWLEDGMENTS

The authors would like to thank Mark Christon (LANL), Jozsef Bakosi (LANL) and Lori Pritchett-Sheats (LANL) for their efforts in assisting the

authors through Hydra-TH installation, Hydra-TH usage, and Hydra-TH V&V document preparation.

References

[1] J. Bakosi, M. A. Christon, L. Pritchett-Sheats, H. Luo, T. Xia, and R. Nourgaliev, *Hydra-TH Verification, Validation and Thermal-Hydraulics Benchmark Problems*, tech. rep., Los Alamos National Laboratories, Los Alamos, New Mexico, LA-UR-11-05387, March 20, 2013.

[2] M. A. Christon, *Hydra-th theory manual*, tech. rep., Technical Report LA-UR-11-05387, Los Alamos National Laboratory, Los Alamos, New Mexico, 2011.