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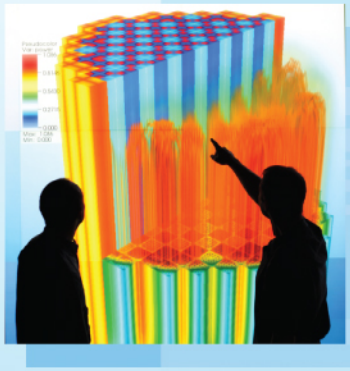

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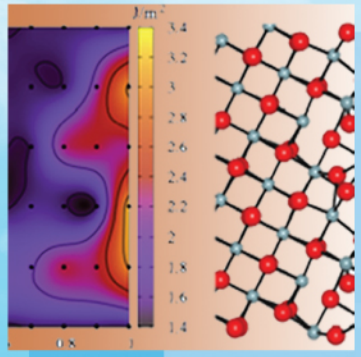

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L3:THM.CFD.P9.02

Native Conjugate Heat Transfer (CHT) in Hydra-TH

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Native Conjugate Heat Transfer (CHT) in Hydra-TH (L3 Milestone THM.CFD.P9.02)

CASL-U-2014-0214-000

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1 Executive Summary

This report describes the work carried out for completion of the Thermal Hydraulics Methods (THM) Level 3 Milestone THM.CFD.P9.02 Native Conjugate Heat Transfer (CHT) in Hydra-TH for the Consortium for Advanced Simulation of Light Water Reactors (CASL).

A critical requirement for modeling water flow past heated fuel rods is the ability to account for conjugate heat transfer effects, or the coupling of heat conduction within a solid and convection within a fluid. A common approach for modeling such flows is to couple a flow solver to a separate conduction solver, iteratively adjusting values at the fluid/solid interface until convergence is achieved. However, this approach requires the problematic coupling of separate codes or solvers and can result in load imbalance in a parallel computing environment. This arises when processors assigned to large flow regions of the domain wait on heat conduction calculations in processors assigned to smaller solid domain regions. To avoid these difficulties, a native conjugate heat transfer capability has been developed within Hydra-TH. In this approach, the mass, momentum, pressure, and turbulence transport equations are solved in the fluid domain while the energy equation is solved across the entire domain (solid and fluid), thereby automatically incorporating the conjugate heat transfer effects into the numerical solution. The requirement with the native approach in this work is that the mesh be conformal along the fluid/solid interface, *i.e.*, the solid elements must share faces with the fluid elements along the interface.

2 Introduction

The primary objectives of this miletone are to implement a native conjugate heat transfer capability within Hydra-TH, demonstrate this capability with comparison of Hydra-TH calculations to known data, and document the work and results. The requirements specified at

the project outset were:

- Conformal meshing at solid/fluid interfaces
- Consistency with turbulence models at solid/fluid interfaces
- Native CHT software should provide expected solution when the energy equation is not solved.
- ALE compatible (support rigid body motion)
- Thermal solver consistency in limit of no flow
- Matching of direct thermal conditions in limit of high conductivity
- Specification of Dirichlet temperature boundary conditions in solid
- Specification of temperature or heat flux at fluid-solid interface (convenience)
- Consistency of nodal field delegates
- Parallel
- Functional in both semi- and fully-implicit projection
- Extensible to multiphase for Phase-2 CASL work
- Extensible for non-matching (non-conformal) fluid/solid interfaces
- Specification of velocity and temperature initial conditions by material, block, user-defined function, or global definition

These requirements steered the design and subsequent implementation. Due to time limitations, specification of temperature conditions at solid/fluid interfaces was not implemented, and testing with fully-implicit projection was not attempted.

The milestone required completion of the following tasks:

- Development of a prototype native CHT capability to test the solution of the Navier-Stokes equations in both fluid and solid regions
- Implementation of a "rigid" material description and the automatic detection of fluid/solid interfaces
- Implementation of a penalty method to constrain flow quantities within the solid materials
- Modification of turbulence models at fluid/solid interfaces
- Penalization of pressure within solid regions
- Modification of the least squares operators to support both fluid-restricted and full-mesh calculations for momentum and energy solves, respectively
- Selection and development of a CHT test problem with addition to the regression test suite

- Application of user-defined boundary conditions with control file function description for CHT test problem setup
- User manual documentation
- Submission of this report

Some of these tasks are briefly discussed in §3, while summary and a discussion of future work are given in §4.

3 Milestone Accomplishments

The initial task involved the demonstration of a prototype native CHT capability to expose the underlying capabilities in Hydra-TH to solve coupled momentum and energy problems across fluid and solid domains. This was accomplished by setting up a lid-driven cavity problem where the cavity walls were replaced with meshed solid regions. These solid regions were made distinct from the fluid regions by setting the density and viscosity to exceedingly high values (to force the calculation of zero velocities in the solid). Temperature boundary conditions were applied on the exterior of the solid regions such that energy would be conducted through the solid adjacent to the exterior hot wall and then convected into the fluid. Although this approach would not be practically viable for solving large-scale problems (due to numerical stiffness issues), results indicated the viability of pursuing a native CHT capability in the code.

The native CHT approach developed here involves the identification of *rigid* (solid) materials in the problem. Internal interfaces separating rigid and non-rigid materials are automatically identified, and the energy equation is solved to obtain the thermal field for the rigid materials and fluid materials simultaneously. A penalty approach is utilized in the solution of the momentum equations to appropriately constrain velocities in the rigid materials to the value specified in the control file (default = zero). Similarly, both pressure and turbulence transport are penalized in the rigid materials. Boundary conditions on velocity for momentum solution, normal distance for turbulence transport, and the modified kinematic turbulent viscosity for the Spalart-Allmaras turbulence model are automatically created along the internal interfaces. No user specification is required for these interface boundary conditions. The associated inefficiencies with this approach, *e.g.,* solving momentum equations in regions where the solution is not needed, were considered acceptable in comparison to the software development expense of alternative approaches, but these inefficiencies have not been quantified.

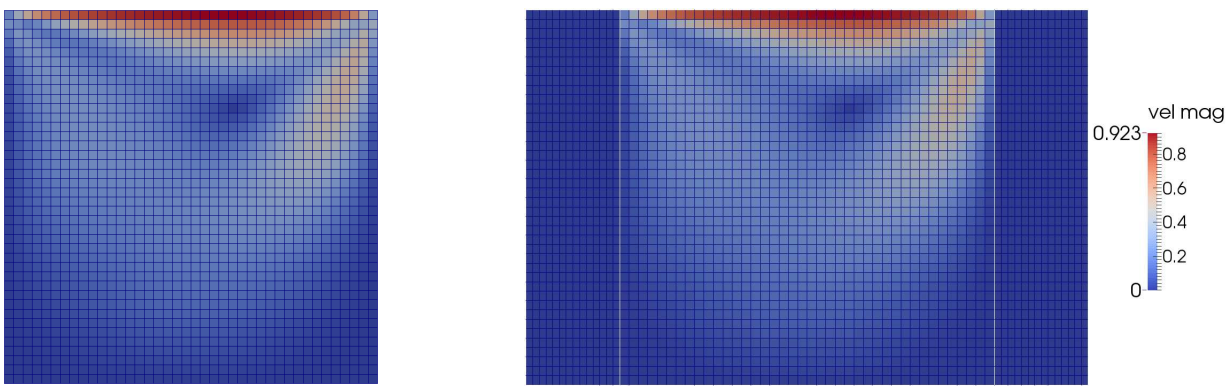
An example of the control file specification of conjugate heat transfer is shown in Figure 1. Here, the solid material is identified with the use of the *rigid* keyword (default = *off*), and the specification of the rigid material velocity components is made with *velx, vely, velz* keywords (default = 0.0). Activation of any form of the energy equation automatically enables conjugate heat transfer across any rigid/non-rigid interface.

The majority of effort in this milestone centered around obtaining correct flow solutions in the presence of internal interfaces. This required creation and application of appropriate boundary conditions along the internal interfaces, as well as construction of interface-aware least-squares operators. A calculation comparison for a laminar, lid-driven cavity is shown in Figure 2. The calculation on the left is a lid-driven cavity with no-slip boundary conditions applied on the external vertical walls and bottom wall. On the right is the same cavity

```
# Energy Equation
energy temperature

# solid material
material
   id 1
   ...
   rigid on
   velx 0.0
   vely 0.0
   velz 0.0
end
```

Figure 1: Conjugate Heat Transfer Specification in Control File



(a) Standard boundary conditions (b) Rigid material blocks with interface boundary conditions

Figure 2: Lid-driven cavity (velocity magnitude)

but with vertical walls bounded by rigid material. Along this interface, no-slip boundary conditions are applied, and as required, flow solutions for the two cases match identically.

To assess the CHT implementation, a test problem with analytic solution was selected for comparison to Hydra-TH calculations [1]. This problem involves fully-developed forced convection in an infinite plane-parallel channel bounded by solid walls of a finite thickness. Temperature conditions are prescribed on the exterior wall boundaries, and heat conduction within the solid is coupled to forced convection in the fluid. The problem schematic is shown in Figure 3. The temperature condition prescribed on the exterior boundary is a periodic function of the longitudinal coordinate, with average value T_0. The inlet velocity boundary condition is prescribed with the Poiseuille velocity distribution. The fluid temperature distribution is obtained analytically by expressing the energy balance equation as a complex-valued hypergeometric confluent equation.

A Hydra-TH calculation was run with problem parameters (described in [1]) given by: $Pe = 100$, $\sigma = 1.2$, $B = 100$, and $\gamma = 3$. The inlet velocity distribution (left boundary) was prescribed in Hydra-TH with the new user-defined function capability. Boundary conditions for the temperature at the inlet were set using the hypergeometric confluent equation. The calculated nondimensional temperature is shown in Figure 4. The scale range has been reduced to visually enhance the effect of the flow on the conduction in the solid walls, and the conjugate nature of the flow is evident.

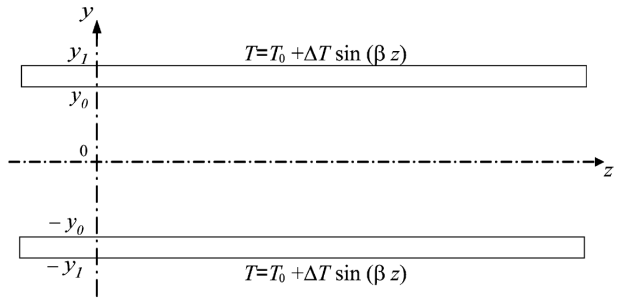


Figure 3: Plane-parallel channel schematic

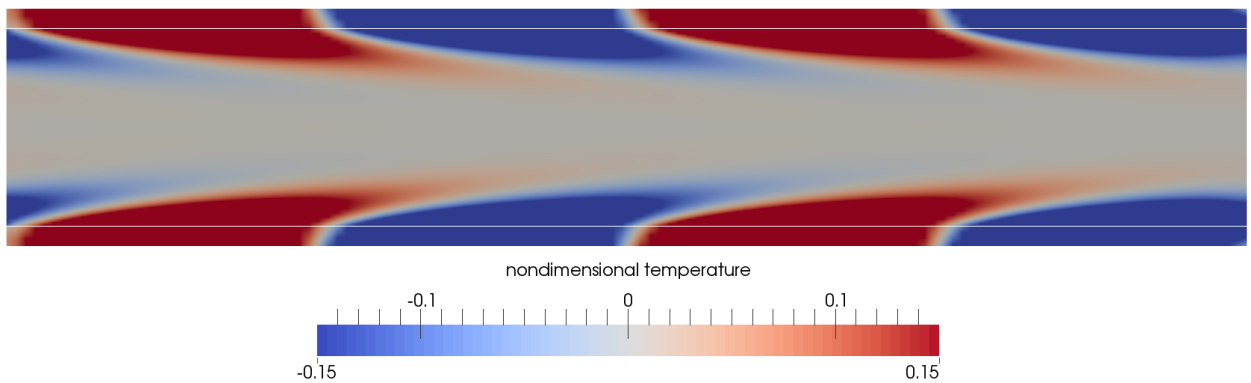


Figure 4: Hydra-TH Nondimensional Temperature for Plane Channel

The analytic solution is compared to Hydra-TH calculations in Figure 5. Coarse, medium, and fine meshes have 42, 168, and 672 fluid elments and 3, 12, and 48 rigid elements in the spanwise direction, respectively. In the longitudinal direction, the meshes have 131 elements. Along the fluid/solid interface, the analytic solution for nondimensional temperature is of the form: $\theta = \theta_1 \sin(x) + \theta_2 \cos(x)$, where x is the nondimensional distance from the inlet. Agreement between Hydra-TH calculated values and the analytic solution is excellent. The period is matched exactly; however, some discrepancy is observed near temperature maxima and minima. Numerical experiments indicate that the solution quality improves with increased resolution in the spanwise direction (as indicated in the figure). Interestingly, solution quality of the plotted quantity is independent of resolution in the longitudinal direction. The degree of mesh resolution needed to match the maxima and minima is somewhat surprising, and additional studies are needed to improve understanding.

4 Summary and Future Work

A native conjugate heat transfer capability has been developed within Hydra-TH. The code automatically detects interfaces for these calculations via use of the *rigid* keyword in the material description. Conjugate heat transfer calculations are handled automatically for all interfaces separating rigid and non-rigid materials in cases where the solution of the energy equation is activated.

To support this milestone, a capability to enable specification of user-defined boundary conditions was added (THM.CFD.P9.05), and this capability was extended in this milestone

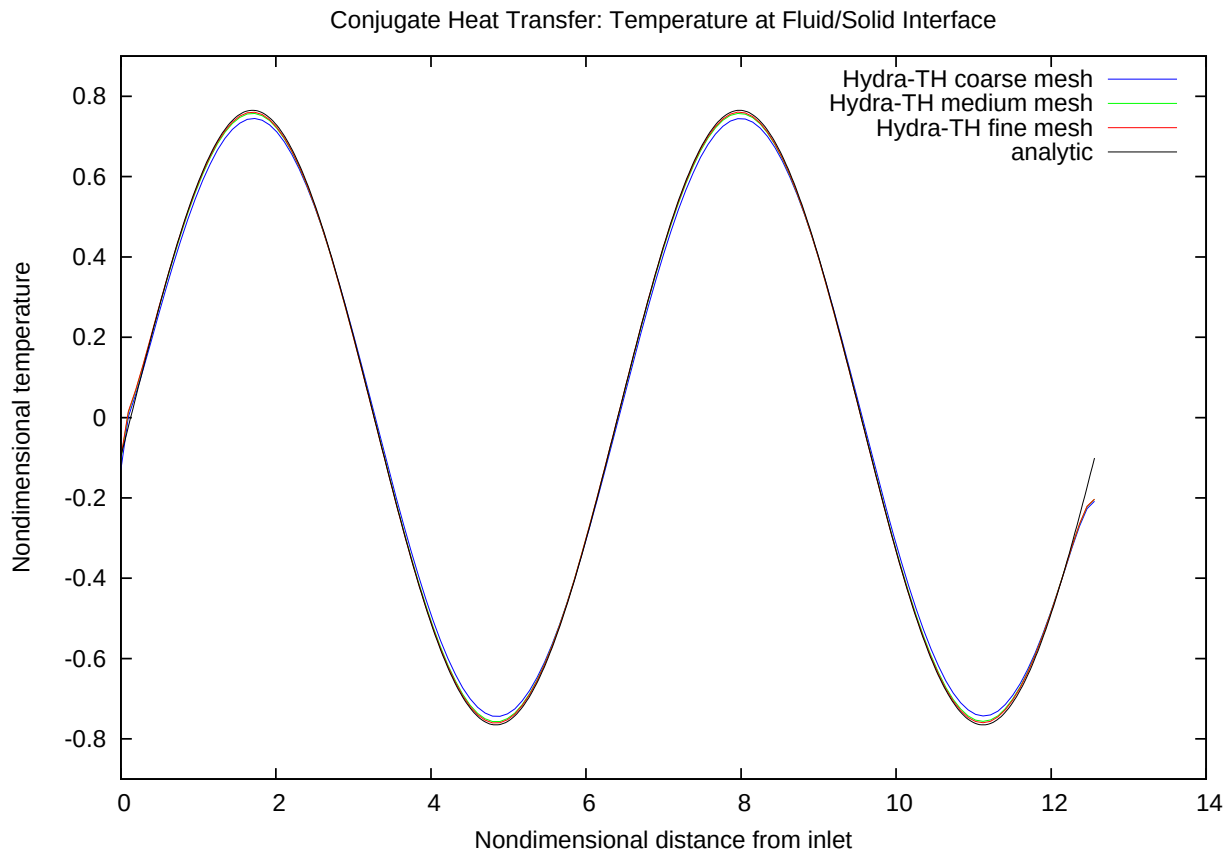


Figure 5: Comparison to Analytic Solution

to allow function specification within the control file for several classes of functions (for both initial and boundary conditions). Also, enhancements were made to give the user direct control over these conditions by global specification, by block, and by material.

A conjugate heat transfer test problem was selected to demonstrate correct implementation of code capabilities. Comparison of Hydra-TH calculations to the analytic solution yielded excellent agreement, with convergence to the analytic solution being observed with higher mesh resolution in the spanwise direction (normal to the flow).

Although this milestone focused on delivering a heat transfer capability, relatively little time was spent dealing with energy equation issues. Rather, the most difficult aspects centered on the generation of correct flow solutions in domains with internal boundaries (interfaces). The most difficult task by far in this area was the modification of the least squares operators so that solid element and edge quantities are appropriately ignored or included for flow solution and energy solution gradient calculations, respectively. The code modifications required for all the tasks were pervasive and extended beyond what was initially anticipated in terms of time and level of effort.

Although code capabilities have been added and tested, a calculation is needed to demonstrate native conjugate heat transfer for a realistic rod bundle configuration. The intended calculation will utilize the HEXPRESS/Hybrid meshing tool, which is capable of meshing both solid and fluid regions conformally. Performance and scalability studies of conjugate heat transfer calculations are needed as well. In addition, testing of the capabilities with fully-implicit projection has not been done but is being planned for future work.

References

[1] A. Barletta, E. R. di Schio, G. Comini, and P. D'Agaro, *Conjugate forced convection heat transfer in a plane channel: Longitudinally periodic regime*, International Journal of Thermal Sciences, 47 (2008), pp. 43–51.