RELAP5-3D Coupling with STAR-CCM+

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CD-ADAPCO has developed a socket-based coupling method between RELAP5-3D and STAR-CCM+.

Increased leverage from modeling and simulation to quantify local behavior within large scale reactor systems is broadly viewed as essential to the viable development and deployment of advanced reactor designs. The concept of coupling the multi-dimensional nodal network approach of RELAP5-3D with more fully resolved and general solution of Navier-Stokes, i.e., computational fluid dynamics, to support this and other needs has evolved over more than a decade, largely in step with the capacity for practical transient analyses at relevant geometric scale and complexity via the latter. Most recently, a generalized infrastructure and user interface for coupling RELAP5-3D with the commercial computational fluid dynamics software, STAR-CCM+, has been developed by CD-adapco in collaboration with the NGNP program at Idaho National Lab. The coupling is assimilated into STAR-CCM+ v7.06 and later releases. RELAP5-3D version 4.0.x or later is required.

In addition to detailed 3D simulation of flow fields, the coupling with STAR-CCM+ brings advantages even in thermal simulations. For example, STAR-CCM+ can accurately model thermal radiation in complex cavities and impose the radiative heat loads as boundary conditions on surfaces. Heat transfer by natural and forced convection can also be accurately modeled based on the actual flow conditions without the need to specify heat transfer coefficients.

The STAR-CCM+ / RELAP5-3D linkage advances the technology for transient analysis through a general two-way explicit coupling that supports independent time step specification for each code. RELAP5-3D and STAR-CCM+ are run as separate programs, with each program responsible for its own input / output. A concise and extensible communication protocol has been defined and incorporated into each to manage solution controls and data exchange at coupled boundaries directly through Sockets. The design of the exchange allows for the transfer of only those data and commands that are recognized by both codes, ensuring forward / backward compatibility between future code versions.

With the coupling activated, STAR-CCM+ starts the specified instance of RELAP5-3D upon initialization and establishes the Socket communications. The RELAP5-3D Heat Structures and Time Dependent Volumes (TDV) & Junctions to be coupled with STAR-CCM+ are identified to RELAP5-3D using an extra input file. These are communicated to STAR-CCM+ and appear as RELAP Zones and RELAP Flow Zones, respectively, for selection and further specification. Corresponding diabatic walls and flow boundaries are also selected from the CFD model and matched to the appropriate RELAP Zones and RELAP Flow Zones, as appropriate, using the STAR-CCM+ GUI.

The coupling supports specified temperature or specified heat flux for thermal boundaries, and mass flow or pressure specifications for flow boundaries. Mass flow is assumed to be single phase at the present time, but may be multi-species.

At the initial time step, each code executes with assigned boundary conditions. Boundary conditions are then updated for the next time step by exchanging required solution variables at the

coupling plane. Solution variables are appropriately distributed or averaged to and from STAR-CCM+, respectively, to exchange data in a conservative manner. Flow boundary data from RELAP5-3D to STAR-CCM+ may also be distributed across the boundary according to a user-defined profile.

Substantially smaller time steps are generally used for CFD in comparison to RELAP5-3D. Accordingly, solutions are synchronized by linearly extrapolating boundary data for STAR-CCM+ from RELAP5-3D results for two successive time steps of the latter. Sequencing of RELAP5-3D is regulated by STAR-CCM+ and advanced to the next time step as the STAR-CCM+ solution time approaches the RELAP5-3D solution time. Boundary conditions for RELAP5-3D use latest known results from STAR-CCM+.

Parallel processing is also enabled for STAR-CCM+. The Master Process gathers averages from coupled boundaries distributed across multiple processors to send to RELAP5-3D. It also distributes boundary conditions received from RELAP5-3D to the coupled boundaries on multiple processors servicing STAR-CCM+. Since the solution time for RELAP5-3D is small in comparison with STAR-CCM+, only one instance of RELAP5-3D is required even for massively parallel CFD runs.

A simple test model representing the Natural Convection Shutdown Heat Removal Test Facility (NSTF) configuration for the VHTR Reactor Cavity Cooling System (RCCS) design concept was modeled and analyzed to demonstrate the co-simulation capability. The test model is shown in Figure 1. Fluid flow and heat transport in the RCCS channels and channel walls, which are shown with the inlet at the bottom, were modeled with RELAP5-3D with each channel and channel wall represented as a separate TDV and heat structures. A heated wall representing the reactor side of the cavity and the opposing unheated containment wall with adiabatic exterior were similarly included as RELAP heat structures.

FIGURE 1: STAR-CCM+ / RELAP RCCS DEMONSTRATION COUPLING

STAR-CCM+ And RELAP Models, Showing Boundary couplings
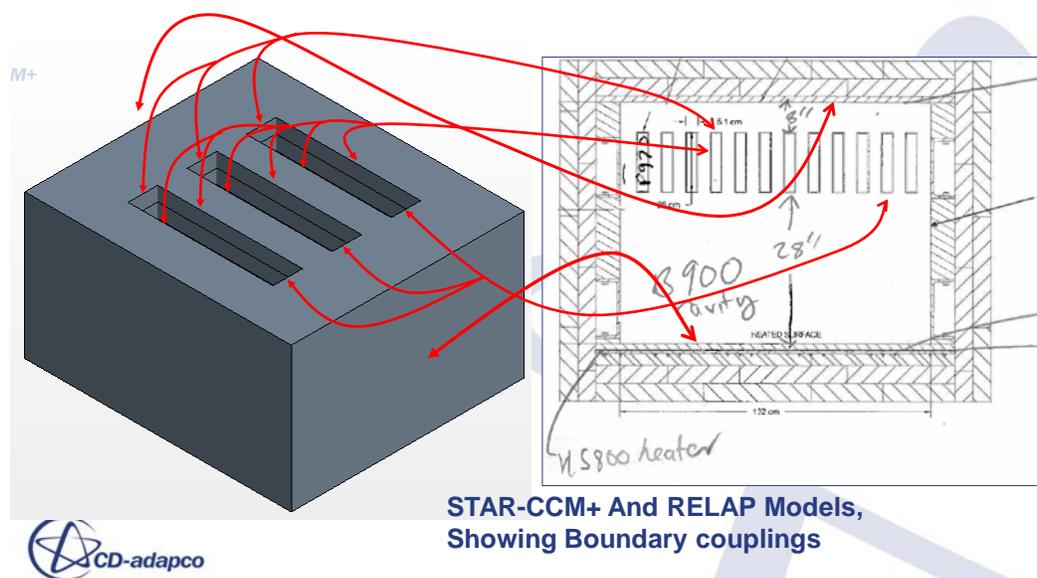
Natural circulation flow and heat transfer in the enclosed air-filled cavity surrounding the cooling channels was modeled using STAR-CCM+. Air in the cavity was represented as incompressible with Boussinesq approximation for buoyance. The cavity-side surfaces of the RCCS channels, reactor-side heated wall, and containment wall were assigned as separate temperature thermal boundaries in the coupled RELAP5-3D / STAR-CCM+ analysis with association shown in Figure 1. As such, mean boundary temperatures were calculated in RELAP5-3D and imposed on the coincident STAR-CCM+ locations. In STAR-CCM+, concurrent local heat fluxes were calculated, averaged over the corresponding descretized sub-boundaries of RELAP5-3D, and applied within RELAP5-3D accordingly.

The system was analyzed for a closed cavity to for testing purposes and results are presented. Except for the thermal couplings as previously described, adiabatic wall boundaries were applied on all other surfaces. Note that this analysis is intended for demonstration purposes only.

Figures 2 through 4 show the natural circulation conditions that develop within the cavity as the enclosed air is warmed by the RCCS channels and the heated wall, which were initialized within RELAP5-3D at the same elevated temperature. In the cross-channel direction (Figure 2), air begins to rise adjacent to the heated RCCS channels, with downward flow developing in between the channels and adjacent to the adiabatic side walls.


FIGURE 2: CROSS-CHANNEL VIEW OF DEVELOPING NATURAL CIRCULATION IN REACTOR CAVITY DURING HEATUP
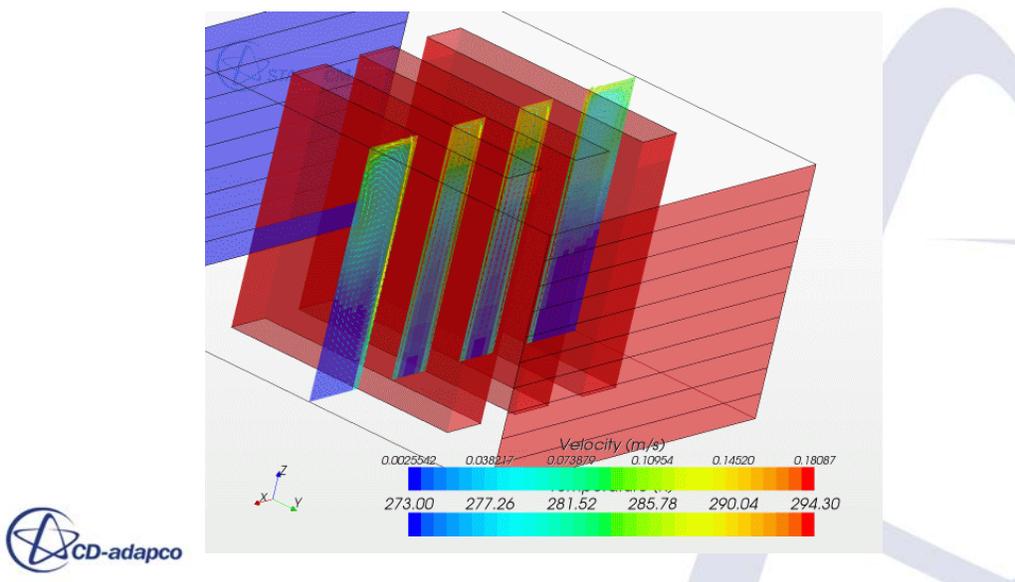
A more complex flow pattern develops in the channel-wise direction (Figure 3), due in part to the asymmetry forming from the reactor-side heated wall and unheated containment wall. Air warms

most rapidly in the relatively narrow RCCS channels. As the warm air rises adjacent to the RCCS channel walls, cooler air is drawn into the channels from the wall regions. Figure 3 shows downward and outward flow developing along the mid-channel line, initially in more or less equal measure toward the heated and unheated walls.

FIGURE 3: CHANNEL-WISE VIEW OF EARLY NATURAL CIRCULATION IN REACTOR CAVITY DURING HEATUP
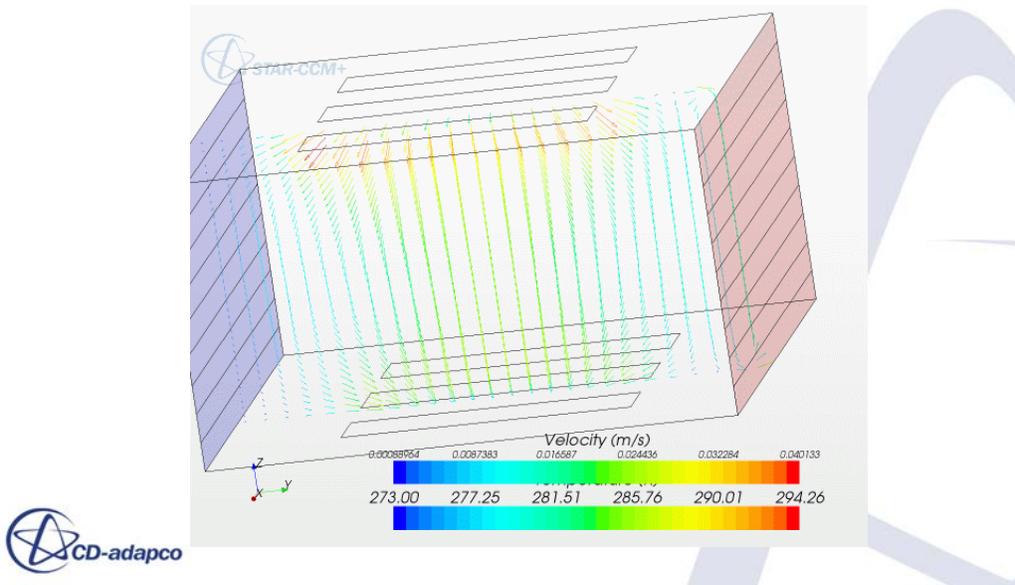
As the air continues to warm, an additional recirculation zone adjacent to the heated wall begins to superimpose on the cavity flow patterns. This is evident in Figure 4. Outflow from the RCCS channels shifts preferrentially toward the unheated wall in response.

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