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High Fidelity Simulations of Air-Cooled Reactor Cavity Cooling System

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ART Advanced Reactor Technologies
GAS-COOLED REACTORS

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Introduction

High Temperature Gas Reactor (HTGR) designs incorporate passive safety systems (e.g., the Reactor Cavity Cooling System [RCCS]) that utilize natural principles to manage heat dissipation from the reactor pressure vessel (RPV) during accidents or routine shutdowns. Regulatory bodies require thorough validation of such safety systems in order to ensure they meet specified standards.

Consequently, the industry is experiencing a pressing need for advanced simulation tools that can accurately assess the performance of these types of systems. In the literature, a knowledge gap exists concerning high-fidelity data for the RCCS, and this gap is one of the areas of focus of the present study. This research focuses on a specific RCCS designed for General Atomics' Modular High-Temperature Gas Reactor (GA-MHTGR). Experimental studies on a scaled version (can be seen in Figure 1) of the air-cooled RCCS used in GA-MHTGR were conducted by the University of Wisconsin-Madison (UW-Madison). This work contributes to a broader initiative aimed at establishing a numerical benchmark based on the UW-Madison experiments.

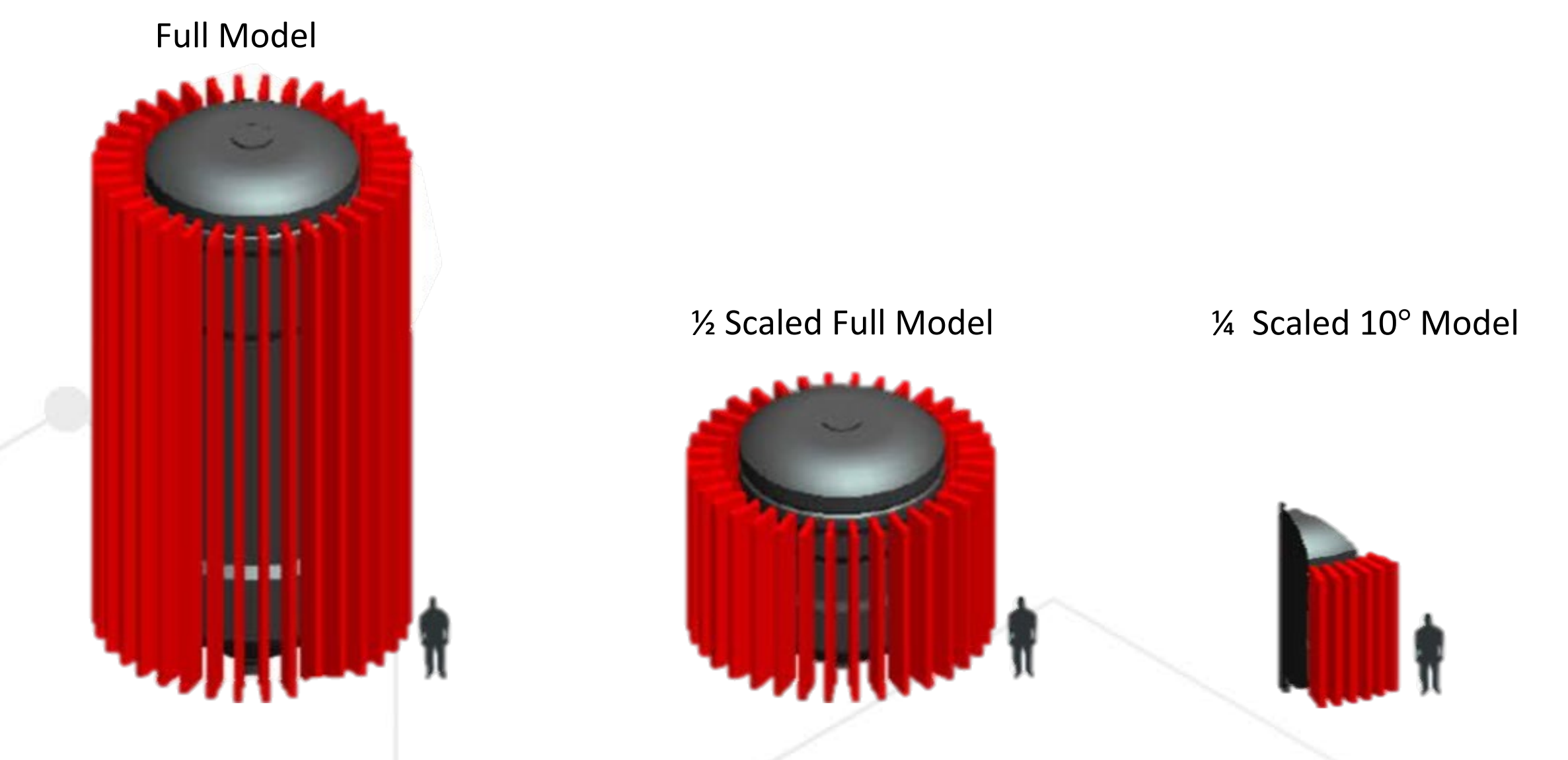

Figure 1: Scaled representation of GA-MHTGR's RCCS

Method

This work will utilize the numerical tools under the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. The current work uses the Cardinal application. Cardinal is an R&D 100 winner code that can wrap the spectral element code NekRS for Computational Fluid Dynamics (CFD) and the MOOSE framework applications, enabling large-scale, first-of-a-kind simulation of energy systems.

The RCCS problem will be solved as a conjugate heat transfer problem. The heat transfer in solids will be modeled using the MOOSE tools (including radiative heat transfer), and fluid flow will be modeled as Large Eddy Simulations (LES) using NekRS. The coupling strategy is presented in Figure 3. The conservation equation for fluid flow is assumed to be incompressible, and the buoyancy force is modeled using the Boussinesq approximation.

$$\nabla u = 0$$

$$\rho\left(\frac{\partial u}{\partial t} + u\,\nabla u\right) = \nabla P + \nabla\cdot\tau + \rho f$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\cdot\nabla T\right) = \nabla\cdot(k\nabla T) + \dot{q}$$

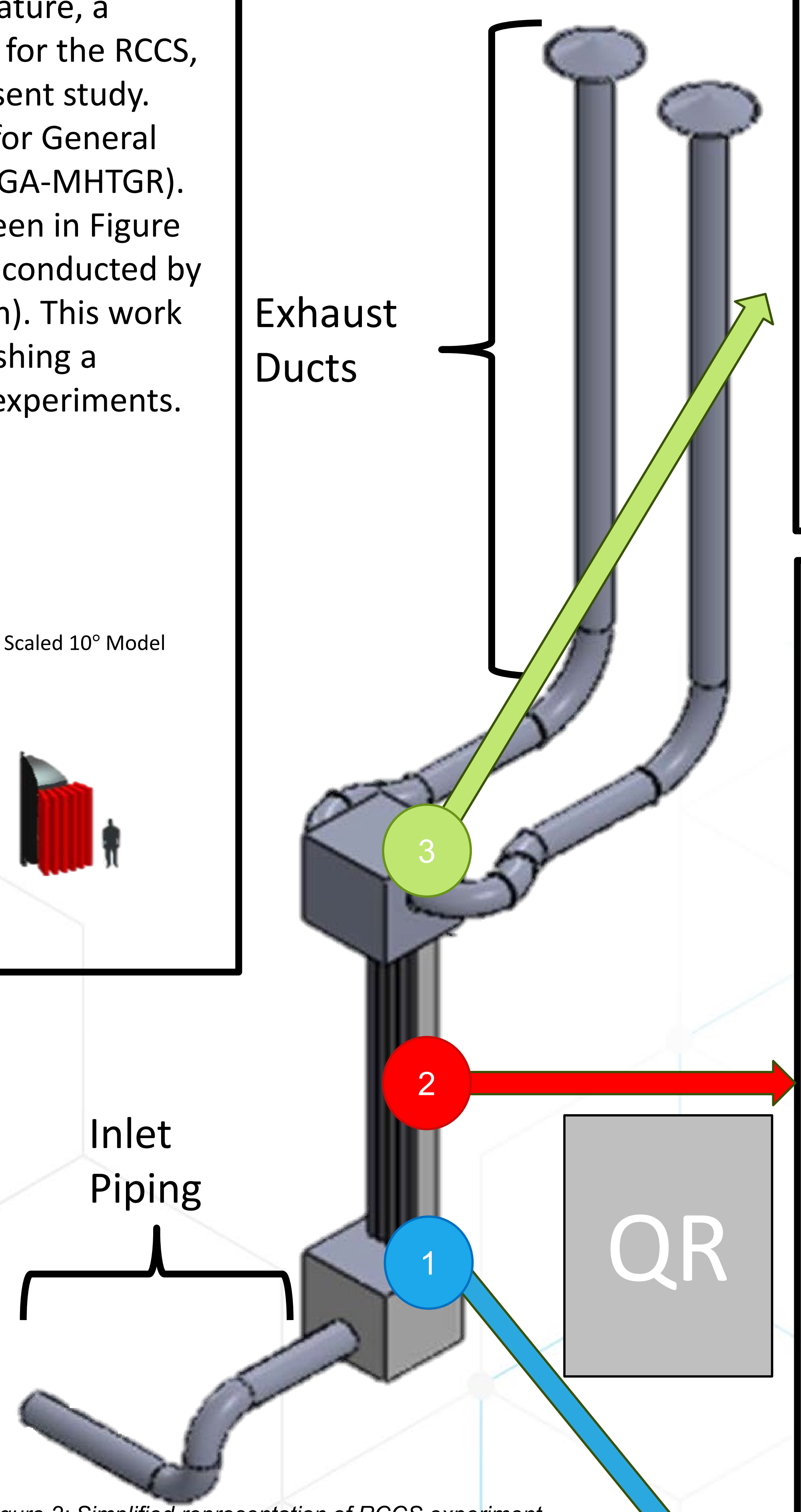

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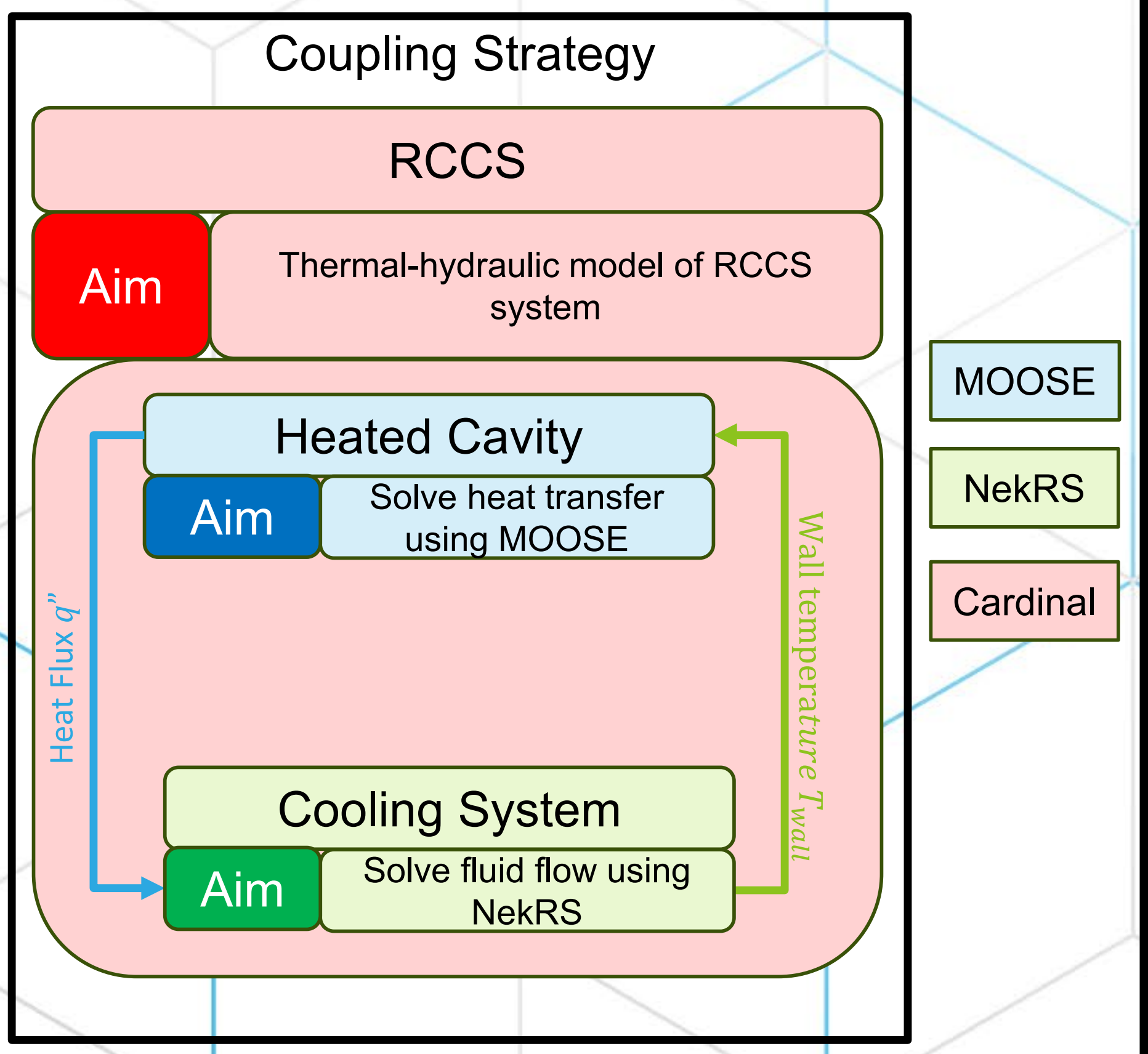
Figure 2: Simplified representation of RCCS experiment (taken from NEUP Report)


Coupling Strategy

RCCS

Aim: Thermal-hydraulic model of RCCS system

Heated Cavity

Aim: Solve heat transfer using MOOSE

Cooling System

Aim: Solve fluid flow using NekRS

Figure 3: Cardinal coupling strategy

Results: Outlet Plenum

The results are produced using the NekRS code. The coupled model is under development. These results show a NekRS thermal hydraulic model using the experimental temperature measurements at the wall as a Dirichlet boundary condition..

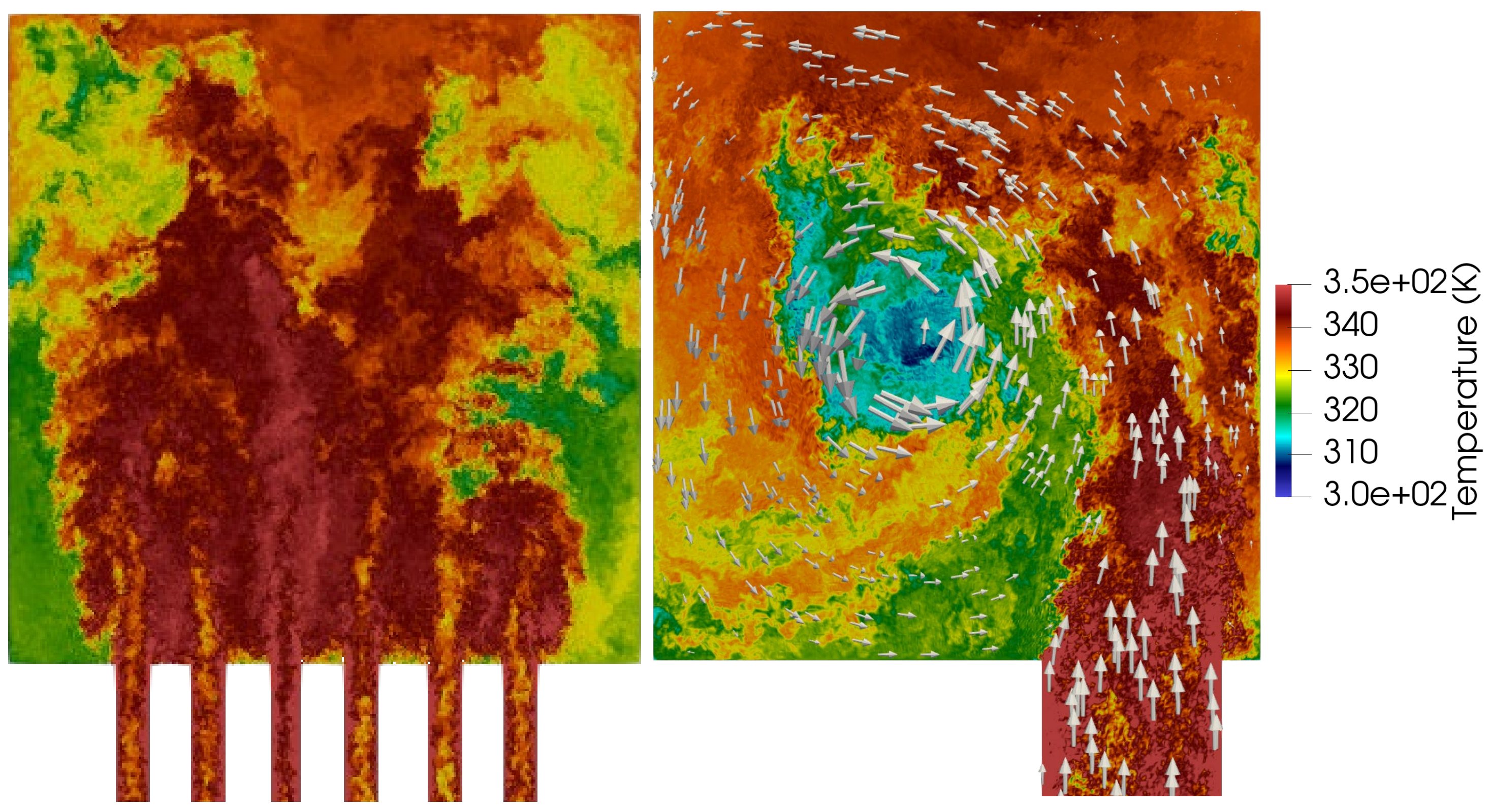


Figure 5: Instantaneous temperature at outlet plenum at left (front view) and right (side view). (White arrows added to side view to show flow direction in outlet plenum).

Figure 5 shows the flow patterns in the outlet plenum. The hot air coming from the riser duct mixes in the outlet plenum and goes into the exhaust ducts. The white arrows on the figure on the right show the flow direction produced from the averaged velocity field. The mixing flow patterns shown in the figure have a significant effect on the heat removal characteristics of the RCCS design.

Results: Riser Ducts

The results in the riser ducts show a consistent behavior of an elongated duct flow as expected. The thermal-hydraulic NekRS model is validated using the experimental data and available correlations in the literature using the partial geometry. The pressure drop is calculated using the available correlations in the literature, with the results summarized in Table 1.

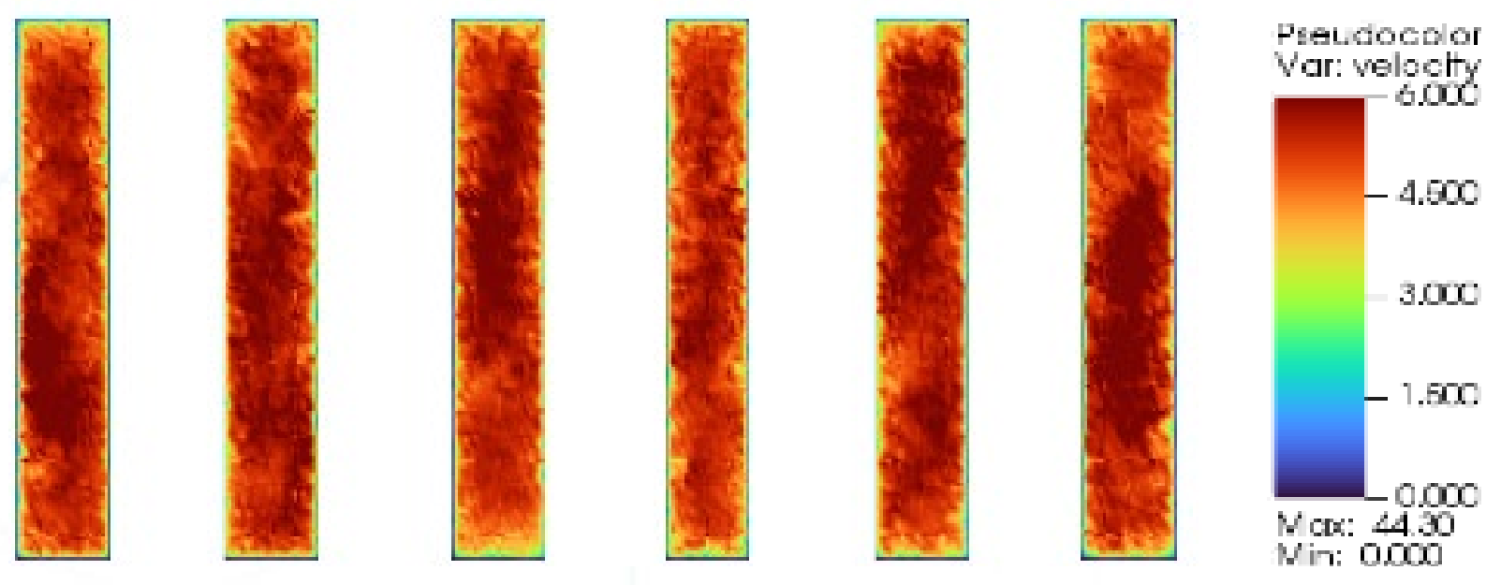


Table 1 : Pressure Drop Comparisons

Method	Pressure Drop (Pa)	Difference
NekRS	**5.71**	**-**
Bhatti & Shah	5.51	**3.5%**
McAdams	5.78	**1.22%**
Colebrook	5.98	**4.64%**

Figure 6: Instantaneous velocity at riser ducts (cross-section view)

The temperature validation can be seen in the figure below. The red dots represent the experimental measurements, and the solid lines show the NekRS results corresponding to the different mesh resolutions.

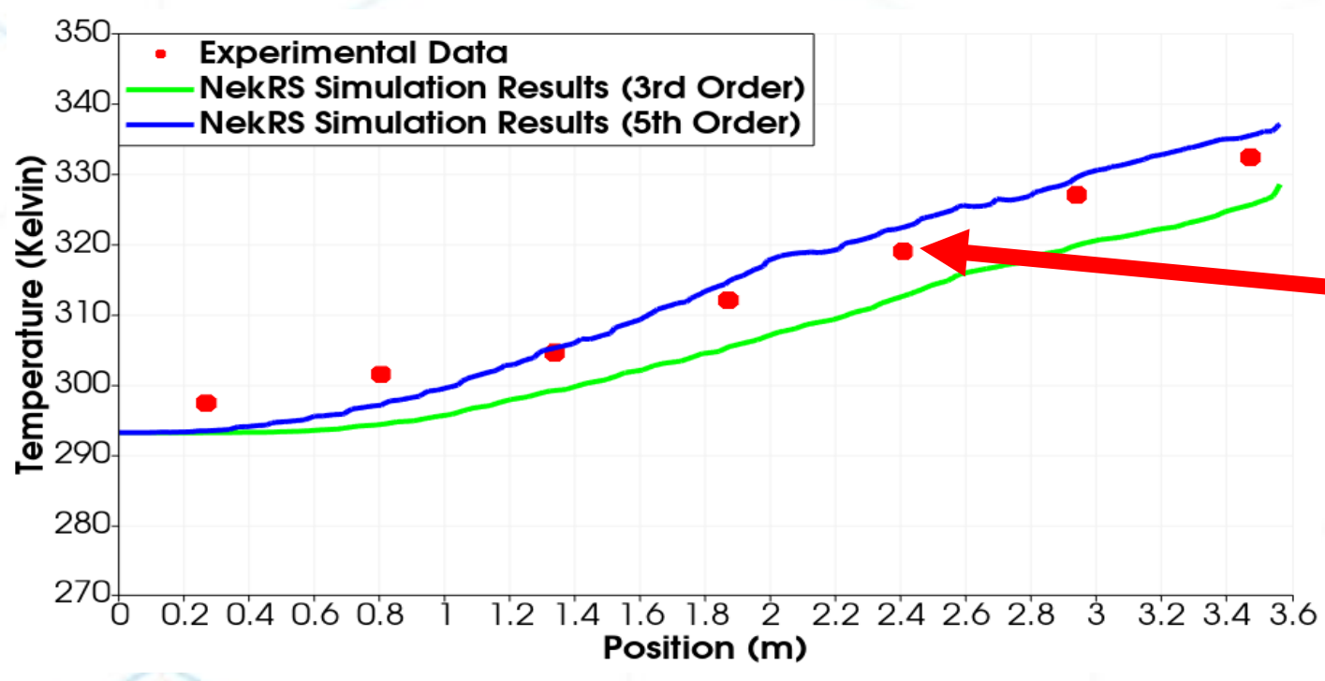


Figure 7: Temperature validation of thermal-hydraulic model

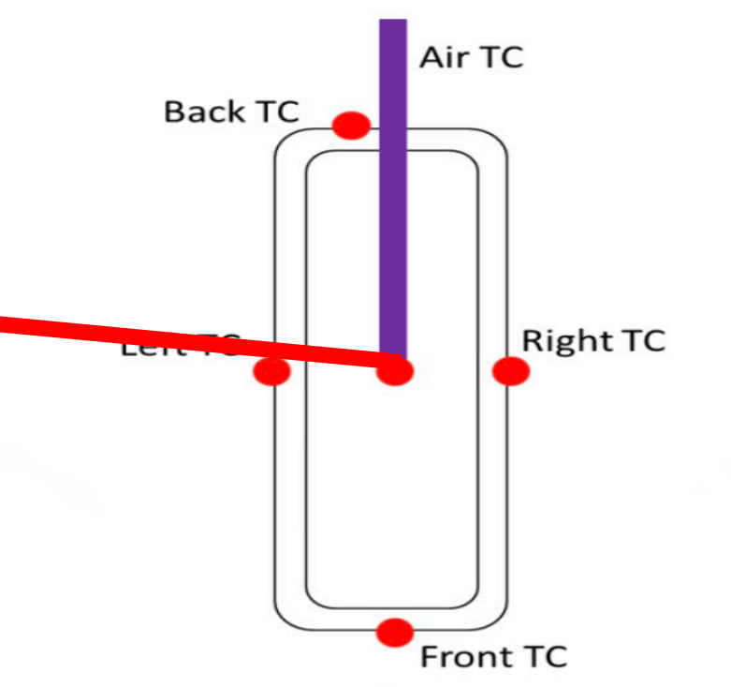


Figure 8: Locations of thermocouples

Results: Inlet Plenum

The air comes from the inlet piping and is drawn into the riser ducts due to the heated airflow inside the ducts.

The model consists 1.7 Million element which corresponds to 3.67×10^8 grid points in the NekRS spectral elements code for a 5th polynomial order solution.

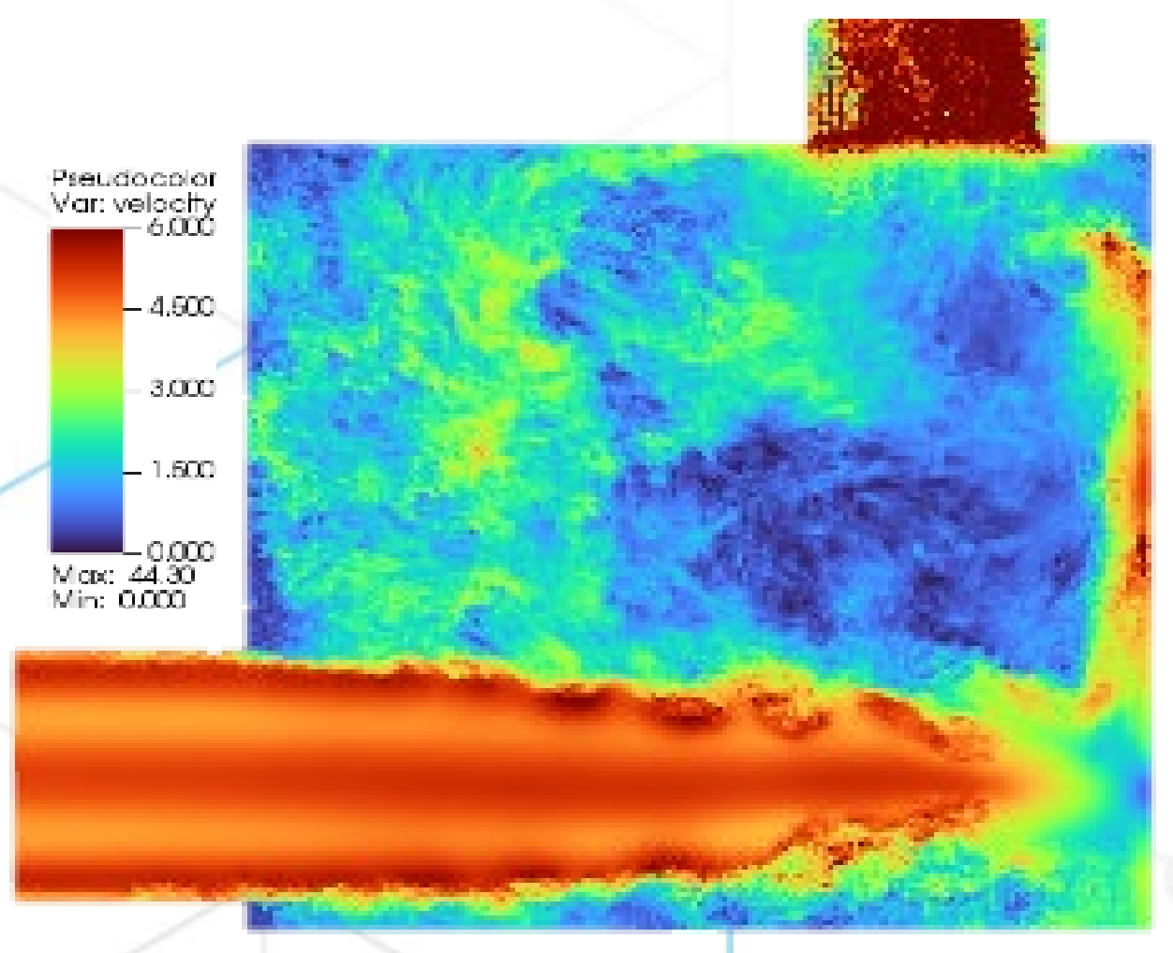


Figure 9: Instantaneous velocity at inlet plenum (side view)

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NEAMS Nuclear Energy Advanced Modeling and Simulation

ART Advanced Reactor Technologies

INL Idaho National Laboratory