3D Magnetohydrodynamics Analysis for Advanced Liquid Metal Blankets

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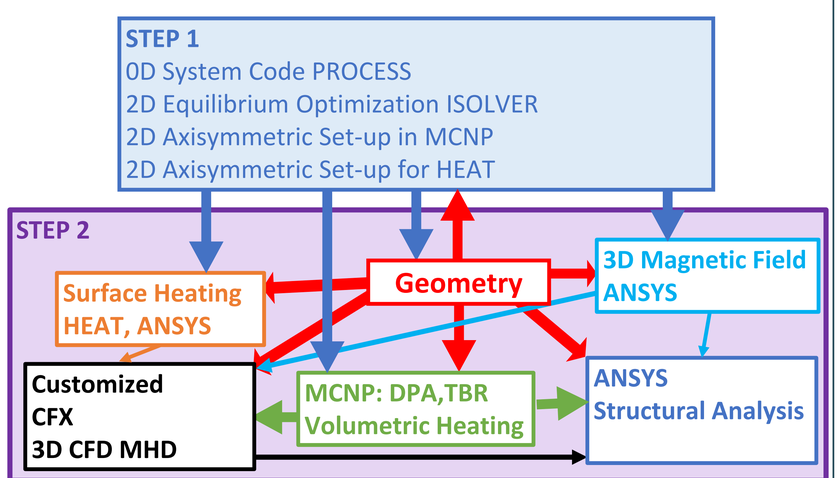
- The development of specialized liquid metal (LM) magnetohydrodynamics (MHD) codes has been a major area of research in fusion programs worldwide. However, these codes are generally not scalable for complex 3D geometries with multi-physics loads typical of fusion applications. Modifying an existing multi-physics computational framework like ANSYS could revolutionize LM blanket development by enabling the modeling of diverse physical phenomena—such as heat transfer, mass transfer, stress analysis, and loading conditions like buoyancy and transient electromagnetic forces—while accelerating the evaluation of design concepts and experimental mockups. This approach leverages ANSYS's advanced numerical methods for meshes and solvers to tackle larger computational problems with enhanced accuracy.

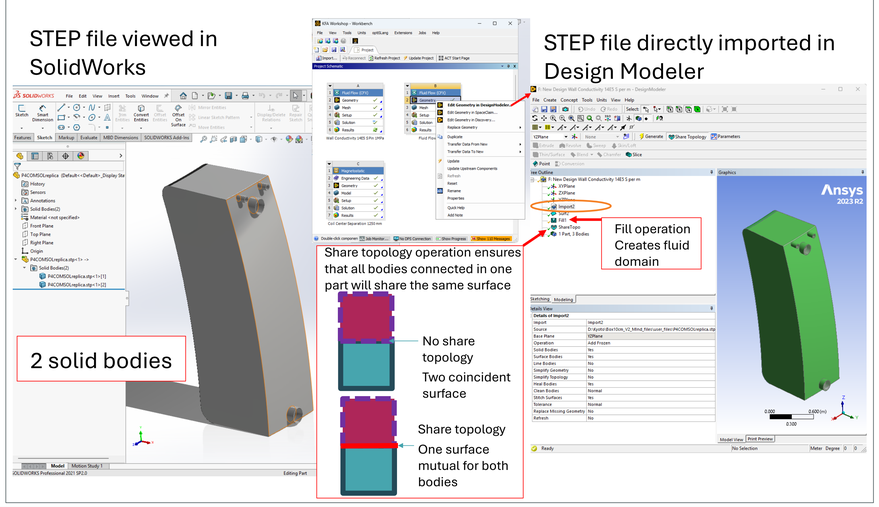
- In this contribution, PPPL used a customized version of the general-purpose computational fluid dynamics (CFD) code, ANSYS CFX, to advanced LM blanket concepts, characterized by a wide range of electrical conductivities and external magnetic field loads. Codes were customized to achieve robust convergence and validated solutions for MHD flows at high external magnetic fields characterized by Hartmann (Ha) numbers of the order of many thousands. Special modification will be used for flows with MHD turbulence, which occur in regions of lower Ha and higher Reynolds (Re) numbers. Analytical and experimental results for flows in circular pipes across a wide range of external magnetic fields and wall conductance levels were used to validate the MHD analysis method. The validated CFD MHD code isused to simulate the performance of Kyoto Fusioneering's (KF) silicon carbide composite (SiCf/SiC) blanket concepts. This simulation will account for variable external magnetic fields, neutronic volumetric heating, and surface heating on plasma-facing shielding components. A mock-up design with necessary instrumentation will be tested by KF at UNITY-1, the blanket component test facility, to experimentally validate the models applied in the analysis.

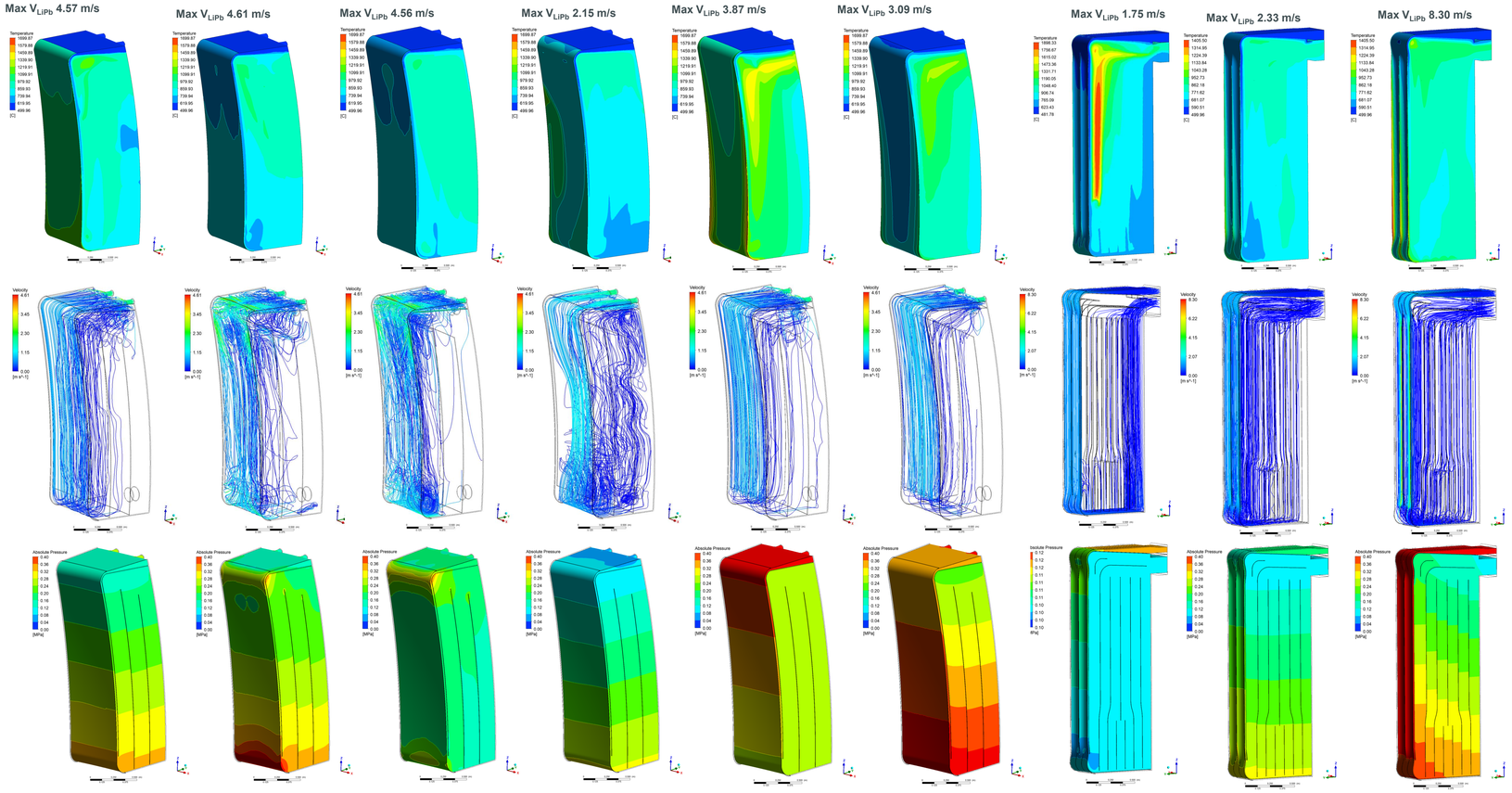
Creating Digital Twins: PPPL Virtual Prototyping System

- **The new system combines physics and engineering codes.**
- The results of the development of a virtual prototyping system for numerical analysis of liquid metal blankets for future fusion devices are reported.
- The new system has a two-step workflow for rapid design and optimization of the blankets:
  - Step1: 0D, 1D, and 2D codes will be used to optimize initial design build.
  - Step 2: 3D geometry of the power plant is finalized, and blanket design is created, using the optimized equilibrium shape of the plasma. 3D geometry together with 3D external loads are used in the detailed 3D Computational Fluid Dynamics (CFD), Magneto Hydrodynamics (MHD) analysis performed using customized version of ANSYS CFX, and detailed structural analysis using ANSYS structural code modified to include effects of irradiation induced swelling.



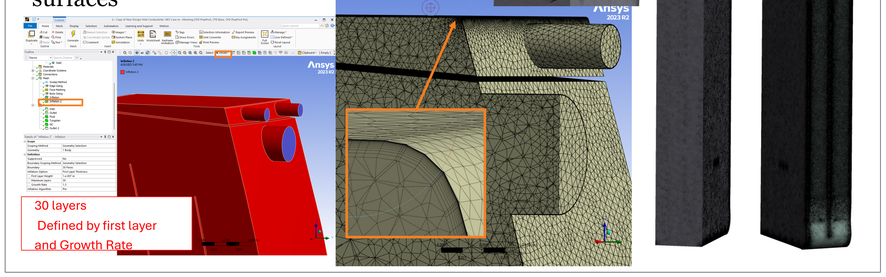
Direct Geometry Input



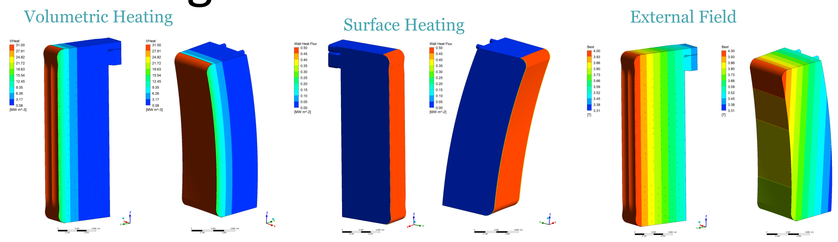


Automatic Meshing Procedure

Inflation on fluid domain is required for proper resolution of boundary layers
Box mode can be used to select all surfaces



Loading of CFD MHD



- Virtual Prototyping System Allowed analysis of complex 3D geometry
- Magnetic Induction MHD model showed significant effect of induced field on flow and heat transfer in the blanket with SiCf/SiC walls
- Further parametric studies will allow to accumulate a database for surrogate model training

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