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The effects of a variable interface permeability on a one-domain VANS model

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Space exploration has aimed to visit other planets and sample cosmic bodies within our solar system in the past decades. As these ambitions increase, new technologies and the development of lightweight porous materials are needed to design spacecraft Thermal Protection Systems (TPS) that endure the harsh environment of hypersonic atmospheric entry and ensure the safety of the payload. Current methods used to design the TPS decouple the flow phase from the material phase, hindering the capturing the physics at the interface and, therefore, cannot capture coupling effects between each phase.

The interactions between the aerothermal environment and the material response result in highly coupled, multi-physics problem and are key challenges in optimizing design margins and mission risk. The equations governing the Thermal Protection Material (TPM) phase are tightly coupled to the equations governing the flow field (the environment phase) at the interface of the two domains. Historically, three general strategies have addressed the flow/material coupling problem. In increasing order of fidelity, we can enumerate these strategies in terms of numerical solvers:

1) decoupled, standalone solvers for material and flow domains,
2) weak or strong coupling between standalone solvers, and
3) unified or one-domain solvers.

To consider both phases in the same computational domain, one must account for the multi-scale aspects of porous media structures. Since it is not feasible with current computational resources to resolve the macro and micro scale in the same domain, we must locally average the governing equations using Volume Average Navier-Stokes (VANS) equations [Wh199, QW1994]. The averaged equations are closed by employing effective transport properties. In this poster, we present the development of a one-domain VANS formulation for the conservation of mass and momentum for both fluid and porous phases, allowing intrinsic coupling between them. We have included the variable permeability across the interface of both phases derived in [Br2004], enabling the closure of the macroscale equations. Compared to a sharp permeability variation, the variable permeability closure significantly impacts the flow field macroscopic properties such as average velocity, pressure drop, and shear stress. For instance, we have predicted in-depth shear stress that the sharp permeability model cannot. This in-depth shear stress can induce mechanical removal inside the material, which is paramount to capture when designing TPS. Moreover, with this approach, one can estimate the jump coefficients between the pure fluid and a porous medium, enabling the closure of the boundary conditions derived by [OT1995] and [VP2013].

The finding of this poster shows the importance of modeling the flow and material in a unified manner and reveals essential aspects that previous coupling approaches cannot. The development of this one-domain model with a proper interface resolution allows for a higher fidelity assessment of TPS response, reducing design margins and mission risks. In the future, we intend to use the filtering approach from [Br2004] to derive effective properties for more complex microstructures relevant to aerospace applications.

Participation

In-Person

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