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Liquid Metal Modeling for Plasma Facing Components

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Liquid metal (LM) plasma facing components (PFC) are considered an attractive design choice for fusion devices including pilot plants. Several liquid metal concepts for the divertor region are currently under development. Lithium or lithium eutectics have a high affinity for tritium and deuterium at low operating temperatures, and provide a low-recycling boundary condition for the core plasma, which can lead to significant confinement improvements. Liquid metals have sufficient thermal conductivity to control their temperature below evaporation point. However LM can also provide vapor shielding of PFC under transient heat loads. On the other hand, electrically conducting liquids are subject to magnetohydrodynamic (MHD) interactions that can disturb the LM and eject its material into the plasma. MHD effects can also laminarize the flow, thereby reducing turbulence and convective heat transport. In addition, MHD drag can impose additional requirements on the LM delivery system across the magnetic field of the device. An important characteristic of fusion relevant liquid metal flow is free surface smoothness and stability. Heat flux from the plasma impacts the liquid surface at a grazing angle, therefore any change of the free surface conditions can dramatically increase the local heat flux density and therefore create excessive evaportion of liquid lithium into the plasma. Solid metallic PFCs can also undergo transient melting in response to high heat flux events such as large edge-localized modes (ELM), unipolar arcs and disruptions. Changes in surface morphology caused by the motion and possible destabilization of the resulting melt layer can lead to a considerable degradation of the PFC longevity and heat-handling properties.
Virtual prototyping has proved useful to address some of the issues outlined above. Modeling of free-surface flows of electrically conductive liquids is facilitated by computational fluid dynamics (CFD) and MHD simulations. Moreover, phase transitions can alter the heat balance and, depending on the time scales involved, resolidification and evaporation can also significantly affect the dynamics of the liquid. Coupling fluid dynamics and MHD solvers to heat transfer enables one to adress such problem fully self-consistently. LM film flow of different thicknesses was analysed.
Numerical tools capable of simulating flows and heat transfer in the free-surface MHD flow were developed at PPPL based on the customized ANSYS code. MHD is introduced using a magnetic vector potential approach. Free-surface flow capabilities are available in the code and were tested. Electro-magnetic equations are solved in the liquid metal, as well as in the solid components of the structure and plasma. Special stabilization procedures were derived and applied to improve convergence of the momentum equations with the source terms due to the Lorentz force and surface tension.
The same set of numerical tools was successfully adopted at PPPL for modeling atmospheric pressure arcs and was thoroughly validated by comparison with experimental data. Recently we adapted the model to simulate transient metal melting and splashing under conditions corresponding to unipolar arcs on tokamak PFCs. The numerical solutions accounting for phase transitions, are benchmarked against available simulation results and experimental data.

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