Modelling of PFC melt dynamics

Metallic PFC melting events in contemporary machines as well as future reactors fall under a rather unique regime [1]; **(i).** Due to the limited wetted area, the liquid pools are surrounded by progressively colder solid surfaces so that once the melt is accelerated out of the pool, under the action of plasma-induced forces, it promptly solidifies. This necessitates modelling of the full coupling between the fluid dynamics and heat transfer, in order to capture the constantly evolving melt depth and the strength of the viscous damping correctly. **(ii).** The liquid pools are characterized by a vast scale separation, since they feature extents up to an order of a meter versus 100's micron depths. The 3D description of the severely deformed free surface and moving solid-liquid boundary at extended spatiotemporal scales is computationally prohibitive. The use of the shallow water approximation, justified by (ii), offers a suitable compromise, reducing the dimensionality of fluid equations by one owing to depth-integration of the Navier-Stokes equations. Such averaging makes computations feasible, while retaining sufficient details for an adequate description of the macroscopic melt motion.

The MEMOS-U model is based on applying the shallow water approximation to metallic melts induced by hot magnetized plasmas where phase transitions & electromagnetic responses are pivotal [1,2]. The code solves the incompressible resistive thermoelectric MHD equations within the magnetostatic limit together with the convection-diffusion equation for the temperature. In order to formulate boundary conditions on the free surface, not only the liquid but also the plasma-plus-vapour ambient medium are implicitly treated as immiscible TEMHD fluids. Ultimately, the plasma-vapour effects appear exclusively through the pressure and drag force in the stress balance conditions as well as the incident plasma heat flux and the vapor cooling flux in the boundary condition for the temperature equation. Those plasma properties are quantities extracted from external models or experimental observations; these inputs and their underlying assumptions are critically analyzed [1,2].

In addition, a rigorous description for the bulk current density (dependent on the plasma scenario and material properties) entering the free surface needs to be formulated. In the case of tungsten, owing to its high melting point and moderate work function, the only non-trivial boundary condition for the current continuity equation refers to the thermionic current density that escapes to the pre-sheath. Its estimation constitutes the most sensitive aspect of 'plasma-effects' modelling. This is due to the fact that the escaping thermionic current density simultaneously affects the heat balance (as an effective cooling channel) and the dynamics (through the dominant JxB acceleration) leading to a rather involved overall effect on the results. The MEMOS-U model employs results of dedicated PIC studies which revealed that the transition to the space-charge limited regime and the subsequent strict limitation of the escaping thermionic current density are global characteristics of strongly emitting sheaths also in the presence of inclined magnetic fields [3].

The MEMOS-U model has been tested against multiple dedicated experiments in ASDEX-Upgrade and JET featuring different PFC materials, exposure geometries and plasma scenarios [1,2]. The achieved quantitative agreement confirmed that MEMOS-U accurately describes the main physical mechanisms responsible for shallow melting and the final surface deformation profiles, the latter being the principal quantity of interest in predictive simulations of wall damage in future fusion reactors.

[1] S. Ratynskaia, E. Thoren, P. Tolias, et al, Nucl. Fusion **60**, 104001 (2020)
[2] E. Thoren, S. Ratynskaia, P. Tolias, et al, Plasma Phys Control Fusion (2021), https://doi.org/10.1088/1361-6587/abd838
[3] M. Komm, S. Ratynskaia, P. Tolias and A. Podolnik, Nucl. Fusion **60** (2020) 054002