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Modeling of Macroscopic Melt Layer Splashing during Plasma Instabilities*

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Plasma-facing components in Tokamak are exposed to high-heat loads during abnormal events such as plasma disruptions and giant edge localized modes. The deposited high-heat power can melt their surface, generate vapor clouds, cause emission of macroscopic droplets, with subsequent surface damage and high plasma contamination. Most significant problem might be macroscopic melt removal from a tungsten divertor plate into core plasma during plasma instabilities. The plasma flow and/or Lorentz force can be responsible for this macroscopic melt splashing. Melt layer removal is governed by ablation physics of ejected macroscopic material not by evaporation/ionization physics. One mechanism for the macroscopic loss of a melt layer can be from development and evolution of Kelvin-Helmholtz (K-H) instability. Perturbations of the plasma-liquid interface and development of waves can be produced by the high-speed plasma flowing along a thin melted layer. The K-H instability arising at the plasma-liquid interface can later result in liquid droplet formation and these droplets can be splash into the plasma.

The macroscopic behavior of melt layer under disruptions is not well-understood. The theoretical analyses and computer simulations of the stability of a liquid surface under the plasma impact are very important for understanding the physical mechanisms of splashing and droplet formation. The classical linear stability analysis is used to assess the initial conditions for development and growth of surface waves at the plasma-liquid interface for different flow regimes. The 3D equations of hydrodynamics are analyzed in the terms of normal modes. It is determined that the K-H instability is generated when the inertial forces due to the flow become high enough to overcome the stubilizing effects of gravity and surface tension. Perturbations with wavelengths below ~2-3 cm are suppressed on the surface of a deep tungsten melt due to the surface tension force. This cut-off wavelength increases with the decrease of thickness of a melt layer. The K-H instability is additionally suppressed by the magnetic field acting in the flow direction if the relative flow speed does not exceed the root-mean-square Alfven speed.

A new two-fluid hydrodynamic code is developed and applied to simulate the generation of surface waves, formation of liquid drops and splashing under plasma impact. The 3D two-fluid model treats each fluid separately in terms of independent sets of mass, momentum and energy equations. The formation of surface waves due to the K-H instability is naturally included in this two-fluid model allowing numerical simulation of liquid losses and droplet ejection. The conditions for development and growth of the K-H instability at the interface between plasma and liquid tungsten are investigated. Formation of liquid plumes, fingers, and droplets dragged by the plasma flow is studied. It is found that topological structure of liquid patterns is highly irregular. No surface waves which amplify to form conventional K-H finger-like projections that eventually break off to form droplets or periodic array of compact spanwise K-H rollers are revealed. Instead, the molten tungsten metal is blown out by shear forces acting on the bulk of the melt. Impulse of the plasma flow causes bulk fragmentation of the melt layer with ejection of large particle fragments.

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