Modeling of Macroscopic Melt Layer Splashing during Plasma Instabilities

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Abstract

The thermodynamic components in tokamaks due to plasma instabilities remain one of the most important problems in their successful operation. Macroscopic melt losses from diverse plasma and nearby metal component surfaces are important issues. The classical linear stability analysis and computational modeling are used to predict the onset and growth of surface instabilities for the plasma-liquid metal system. The whole cycle of development of plasma density and breakdown of waves in plasma-liquid metal interface is modeled for the first time. The new physics mechanisms and underlying instabilities are elucidated. The present study shows that plasma density and fluctuations of waves at the plasma-liquid metal interface are related to the melt layer thickness and eventually break into droplets. These results shed light on the physical behavior of a melt layer under plasma instabilities as well as on instabilities and droplet formation.

1. Introduction

Transient heat load due to plasma discharges (20-100 MWm²) and edge-localized modes (ELM-s, ~1-5 MWm²) can evolve diverse materials in tokamak devices [1]. The deposited high heat power can generate vapor clouds, melt plasma-facing materials, cause ejection of debris, with subsequent surface damage and cause serious plasma disruptions [2]. One of the most significant problems during plasma instabilities is the macroscopic melt layer losses from a metallic divertor plate and potential contamination of the core plasma. Melt droplets impinging on metallic structures can cause significant damage, increase of erosion, with subsequent surface damage and cause serious plasma disruptions [2]. The behavior of melt layer under plasma instabilities is well-understood. Description and quantification of processes governing macroscopic melt layer motion and macroscopic losses during the course of plasma disruptions and ELMs is important for development of fusion reactors. Melt layer motion and macroscopic losses are mainly driven by ablation physics of material, and also by convection processes [3]. The development of Kelso-Chervenka (K-H) instability at the plasma-metal interface could be one of mechanisms for the macroscopic loss of a melt layer [4]. The high-speed plasma flowing along a melt surface can produce surface melt perturbations and growth of waves. Breakup of waves can later result in liquid droplet formation and these macroscopic droplets can split into splashes. The theoretical studies and experimental investigations of the impact of plasma or other volatile liquid on metal are very important for understanding the physical mechanisms involved in splashing and droplet formation.

2. Theoretical and Computational Models

2.1. Linear Stability Theory of Plasma-Liquid Metal Flows

- The plasma-liquid metal system is unstable above a critical wavelength λc.
- The instability is caused by the presence of bulk plasma-liquid metal interface.
- The instability growth rate is given by the dispersion relation

\[ \omega = \frac{2 \pi}{\lambda_c} \sqrt{\frac{g}{h_m}} \]

where \( \omega \) is the growth rate, \( \lambda_c \) is the critical wavelength, \( g \) is the gravitational acceleration, and \( h_m \) is the melt layer thickness.

2.2. Simulation of Plasma-Liquid Tungsten Flows

- The simulation is performed using the commercial FLUENT program package [8].
- The computational domain is modeled as a parallel flow of plasma and tungsten with a computational domain size of 10 mm.
- The melt layer thickness is varied from 10 to 100 µm.
- The fluid dynamics equations are solved using the finite volume method.
- The stability analysis is performed using the linear stability analysis.
- The simulations are performed using a mesh with 400x80 cells (step size 25 µm).
- The resulting flow fields are used to study the instabilities in the plasma-liquid metal interface.

3. Analytical and Computational Results

3.1. The Onset of the K-H Instability from the Linear Theory

- The critical wavelength \( \lambda_c \) is given by

\[ \lambda_c = \frac{2 \pi}{k_c} \]

where \( k_c \) is the critical wavenumber.

3.2. Simulation of Plasma-Liquid Tungsten Flows

- The simulation results show that the instability growth rate increases with decreasing melt layer thickness.
- The instability growth rate is given by

\[ \frac{d \omega}{d \lambda} = \frac{2 \pi}{\lambda_c} \frac{g}{h_m} \]

where \( d \omega \) is the variation of the growth rate with respect to the wavelength, \( d \lambda \) is the variation of the wavelength with respect to the wavelength, \( g \) is the gravitational acceleration, and \( h_m \) is the melt layer thickness.


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5. Conclusions

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References


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