Etude théorique et numérique de l'instabilité interfaciale de ballottement dans une batterie à métaux liquides

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Abstract

Liquid metal batteries represent a promising solution for stationary energy storage, particularly in the context of the energy transition. Their entirely liquid composition subjected to a strong electric current and high temperature requires a thorough study of internal flows to prevent short-circuit risks due to hydrodynamic instabilities. This thesis focuses on interfacial instabilities caused by the redistribution of electric current in media with different electric conductivity, which can manifest themselves as traveling or standing waves. The technical challenge associated with the theoretical study of these phenomena is the complexity of the calculations related to the consideration of the three fluid layers, viscosity, electromagnetic effects and edge effects. First, a linear stability analysis was performed to study the effect of viscosity and to a lesser extent of surface tension in an infinite three-layer fluid system subjected to the gravity field alone. This gravity field is the driving force of the so-called Rayleigh-Taylor instability, unlike what happens in liquid metal batteries which are gravitationally stable. This first study allows to characterize the coupling of the interfaces to better understand previously carried out experiments. The results show that the behaviour of the interfaces depends on the coupling parameter: the thickness of the medium layer adimensionalized by the wave number of the perturbation. Direct numerical simulations carried out with the Archer code validated the theory until the non-linear effects were significant and allowed to identify three regimes according to the increasing value of the coupling parameter for a system where the upper interface is gravitationally stable and the lower interface is gravitationally unstable: the succession of two coupled regimes, one dominated by the behaviour of a gravity wave, the other dominated by the behaviour of a Rayleigh-Taylor instability, and a decoupled regime. Secondly, the effect of the magnetic field on interfacial instabilities in an infinite three-layer fluid system was studied. The linear stability analysis, extended to include the first three complexities, allowed to map the stability of the system as a function of a dimensionless magnetic field, taking into account both the magnetic field induced by the electric current inside the battery and an external magnetic field, and the coupling parameter. A critical magnetic field was identified, whose value depends on the densities of the three fluids and the surface tensions of the two interfaces. Viscosity has no effect on this map; it slows down the perturbations without directly affecting the stability condition as expected. Finally, the edge effects and the influence of the magnetic field in a two-layer fluid system were studied using an energetic method. The results confirm the stability criterion obtained by Sele for aluminum reduction cells and lay the foundations for a generalized criterion for the three-layer viscous case including surface tension. New direct numerical simulations with Archer showed that the system remains stable when the Sele criterion is respected, although some behaviours of the interfaces are not fully predicted by existing theory, indicating the need for further research.