M.Phil. in Scientific Computing
Student Project 5
Magneto-Hydrodynamic Instability in a Liquid Metal Battery
Adviser: Professor Hrvoje Jasak

Introduction

This project involves implementation of a Magneto-Hydrodynamic (MHD) model of a liquid metal battery and examination of its performance under normal operating conditions and external disturbance by a magnetic field. The flow model consists of incompressible turbulent flow of two immiscible fluids with significant variation in material properties, separated by a sharp free surface and inclusion of MHD forces in the momentum equation. Electric current distribution is calculated solving a conductivity equation and providing current density distribution.

Problem Outline

Liquid Metal Batteries (LMB) offer a solution for the problem of network-level energy high capacity energy storage for stationary systems, working in synergy with renewable energy sources such as wind or solar energy. In contrast to Li-ion batteries, LMBs offer high capacity, availability for regular use and longevity, based on the fact that battery operation involves electrodes in liquid state, as opposed to diffusion-dominated transport in solid components of Li-ion systems.

LMB consists of one solid and one liquid phase electrode, separated by liquid electrolyte in stratified configuration, with the interface level raising or lowering with level of charge. While cell voltage is typically low, LMB cells can support high currents and are thus susceptible to magneto-hydrodynamically induced instability at the free surface.

The objective of this project is to explore modes and limits of instability of the LMB under the influence of external magnetic fields, originating from other cells in a battery pack.

Tasks

Within the project, the following tasks shall be performed:

1. Literature review of design layout and operating characteristics of LMB cells, following the design of the group of prof. Sadoway (MIT);

2. A detailed description of the transient incompressible turbulent free surface flow model of two immiscible fluids, as implemented in OpenFOAM;

3. Software implementation of the current density equation in fluid-only and conjugate electric field implementation, including the container vessel of the LMB. Possibility of variation in position of electrical current collectors needs to be considered;

4. Implementation of the magneto-hydrodynamic body force in the momentum equation, in a formulation appropriate for LMB operating conditions;

5. Validation and verification of the fluid-only and conjugate electric field solver under charge and discharge;

6. Parametric investigation of transient modes of instability for the LMB, with a focus on stability of the electrolyte free surface and likelihood of short-circuit conditions. This should include variation of load level, current density and thickness of electrolyte layer;

7. Presentation of the results of simulation in comparison with available data from previous and related studies.

Contents of the Report

The report should be based on the following format, for which all information obtained from external sources should be appropriately cited, and a reference list included:

- Literature review of contemporary design of LMB cells, including geometrical characteristics, choice of materials and operating conditions. Identification of other relevant studies of MHD simulations for LMB cells. [10%];

- A detailed formulation of the incompressible turbulent free surface flow model of two immiscible fluids with the MHD model needed to simulate LMB battery physics [10%];
- Software implementation of the current density and MHD model, starting from the existing transient incompressible turbulent free surface flow solver. Software implementation of the conjugate electric field solver in conjunction with the free surface fluid flow solver [15%];
- Validation of the LMB flow model under realistic operating conditions. The results shall show all important variables and behaviour, along with initial data for the test [15%];
- Discussion of results and observed modes of instability, in comparison with other published work. [15%];
- Conclusions and further work, including comments safe operating conditions [10%];
- Credit allocated for quality of write up [25%].

Proposed Literature

Davidson, P. (2001). An Introduction to Magnetohydrodynamics (Cambridge Texts in Applied Mathematics). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511626333

Oliver Wong Ten Yuen. “Liquid Metal Batteries”, Masters Thesis, Cambridge University Engineering Department, 2020

Ambri Ambri battery technology https://ambri.com/technology/

Donald R.Sadoway et al. “Liquid Metal Batteries: Past, Present, and Future” In: Chemical Reviews 113.3 (2012), pp. 20752099. DOI: 10.1021/cr300205k.

Tom Weier and Douglas H. Kelley, “Fluid Mechanics of Liquid Metal Batteries”, Applied Mechanics Reviews, March 2018, DOI: 10.1115/1.4038699

Davidson, P. (2016). “Axisymmetric Flows Driven by the Injection of Current. In Introduction to Magnetohydrodynamics” In: Cambridge Texts in Applied Mathematics, pp. 351-373). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316672853.017

P.A. Davidson and R.I. Lindsay. “Stability of interfacial waves in aluminium reduction cells”. In: Journal of Fluid Mechanics 29.5 (2017), p. 054101. https://doi.org/10.1017/s0022112098001025