NUMERICAL STUDY OF MHD INSTABILITIES
IN LIQUID METAL BATTERIES

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Abstract: Liquid Metal Batteries (LMB) offer a very innovative and promising concept for grid scale energy storage. Coupled with increasingly contributing – and highly fluctuating – renewable energies, they may become a key ingredient for providing energy on demand. LMBs are predicted to be economically very competitive compared to other storage devices – especially for electricity storage on the short and medium time scale. However, for safe and reliable operation, a full understanding of fluid motion in such cells is indispensable. In this paper we focus on the effects of the kink-type Tayler instability in LMBs.

1. Introduction

Liquid Metal Batteries (LMBs) represent a completely new storage concept for grid-scale energy storage. A liquid metal (e.g., Na, Mg) is floating on a second, high-density liquid electrode (e.g., Bi, Sb) – both being separated by an intermediate molten electrolyte. This self-assembling structure of the battery provides a number of distinguished advantages compared to classical batteries, as e.g., fast kinetics, potentially long life time and elevated current densities [1]. The use of abundant raw materials and a simple construction can lead to a very cheap means for stationary energy storage, as increasingly demanded by highly fluctuating renewable energies (wind, photovoltaics). Economies of scale demand for up-scaling these LMBs to a diameter of a meter, or so, in order to reach the desired price of 5-10ct/kWh/cycle. Here is the point where magnetohydrodynamics comes into play.
Reliable and safe operation requires a comprehensive understanding and control of fluid flow in LMBs to avoid interface deformations and to optimise mass transfer. Such flows may arise, e.g., due to thermal convection, electro-vortex flows, interface instabilities or the kink-type Tayler instability (TI) [2]. Arising from an interaction of the battery current with its own magnetic field, the latter one is especially relevant for large cells [3].
In the following we will present simulation results of the TI in one electrode of the battery, estimating the impact on the battery and proposing several countermeasures in order to avoid the TI.

2. Numerical Model

The numerical scheme is described in detail in [4], here we give only a short summary for sake of understandability. Solving the Navier-Stokes equation for incompressible fluids

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \eta \nabla^2 \mathbf{u} + \mathbf{f}_\mathrm{L} \qquad (1)$$

in a cylindrical geometry, we add the Lorentz force term $\mathbf{f}_\mathrm{L} = (\mathbf{J_0} + \mathbf{j}) \times (\mathbf{B_0} + \mathbf{b})$ as source of the instability, with ρ, $\mathbf{u}$, t, p, η denoting the fluid density, velocity, time, pressure and dynamic viscosity, respectively. We split the current density and magnetic field into a static part due to the external current ($\mathbf{J_0}$, $\mathbf{B_0}$) and an induced part ($\mathbf{j}$, $\mathbf{b}$).

The very low magnetic Prandtl numbers of liquid metals and the finite cylindrical geometry make it hard to solve the Navier-Stokes equation and induction equation simultaneously. For that reason we use an integro-differential equation approach by solving a Poisson equation for the electric potential

$$\Delta\phi = \nabla \cdot (\mathbf{u} \times \mathbf{B}) \tag{2}$$

and computing the induced current as $\mathbf{j} = \sigma(-\nabla\phi + \mathbf{u} \times \mathbf{B})$ with σ as the electric conductivity. We obtain then the induced magnetic field **b** by Biot-Savart's law.

3. Characterisation of the Tayler instability in liquid metal electrodes

Simplifying the battery electrode to an infinite long cylinder, the cell current will induce a purely azimuthal magnetic field. While the relevant criterion for onset of the TI in ideal conductors [5]

$$\partial(rB_\phi^{\,2}(r))/\partial r > 0 \tag{3}$$

depends only on the radial dependence of that field, we have to account for the stabilising role of viscosity and resistivity when working with liquid metals. That means that there is a critical cell current for the onset of the TI – which does not depend on the size of the battery.
The TI will appear first in the better conducting liquid electrode, which is typically the upper one. The scaling between different liquid metals is possible via the Hartmann number (here for a cylindrical electrode)

$$Ha = B_\varphi(R)R\sqrt{\frac{\sigma}{\eta}} = I\,\frac{\mu_0}{2\pi}\sqrt{\frac{\sigma}{\eta}} \tag{4}$$

with R and μ_0 meaning the electrodes radius and the vacuum permeability.

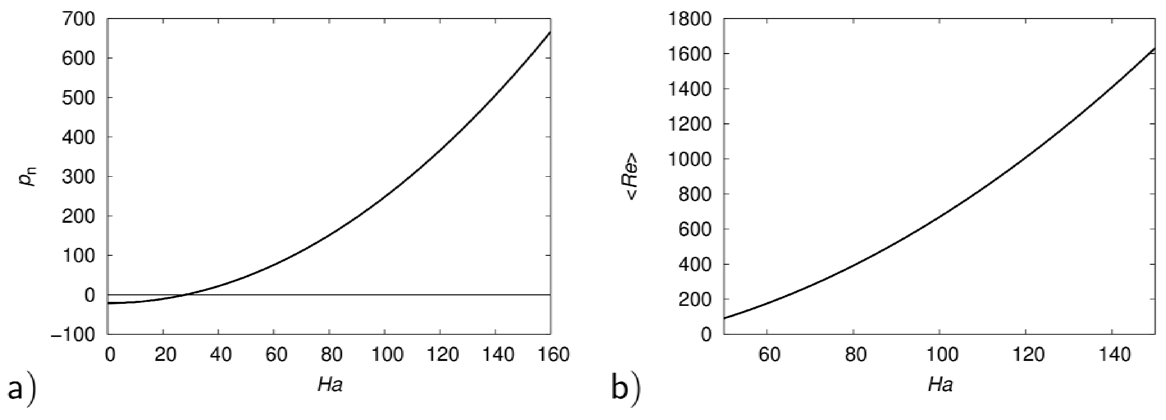

Figure 1: Growth rate normalised by $R^2\rho/\eta$ vs. Hartmann number a), and mean Reynolds number of the TI in saturation in dependence of the Hartmann number b) [6].

Figure 1a) shows the growth rate of the TI in a liquid metal column with aspect ratio height / diameter = 1.2 and a critical Hartmann number for onset of the TI of Ha_{cr} = 29. The Reynolds number $Re = \rho uR/\eta$ of the saturated TI is shown in figure 1b). For typical electrode materials one would expect a few millimetres to a few centimetres per second of maximum velocity in the fluid [6]. Although such flows alone may not be strong enough to shear off the electrolyte layer, their interaction with interface instabilities may indeed pose a problem for the integrity of the stratification.

4. Stabilising the Tayler Instability

In order to maintain the stable density stratification of a LMB and ensure safe operation, the TI should be avoided or at least dampened in the upper electrode.
The simplest measure for taming the TI is placing an insulating rod on the battery axis (figure 2a) [3]. Depending on the diameter, this allows for shifting the onset of the TI to much higher cell currents. Leading the cell current back through a bore in the middle of the battery (figure 2b) allows for totally suppressing the TI.

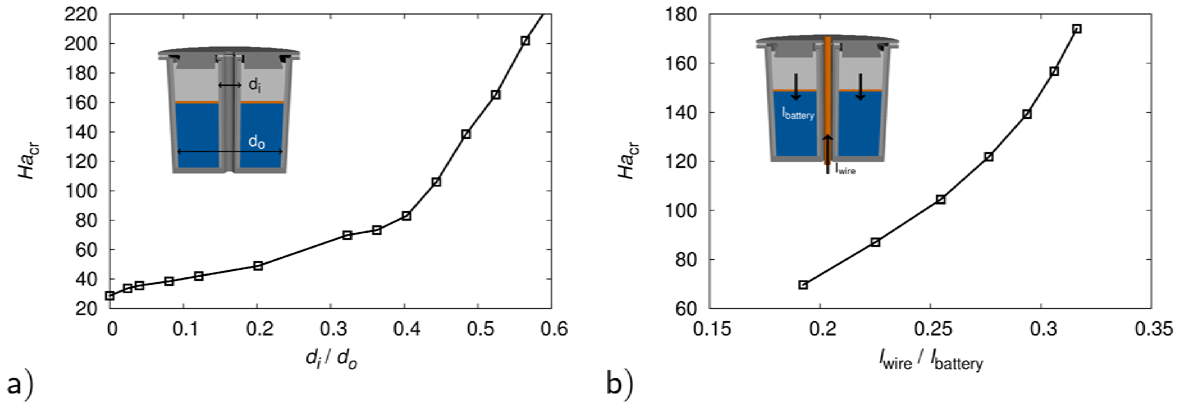

Figure 2: Critical Ha number for onset of the TI for an electrode with aspect ratio 1.2. Either the bore diameter a) or the current flowing back through the bore b) is varied [6].

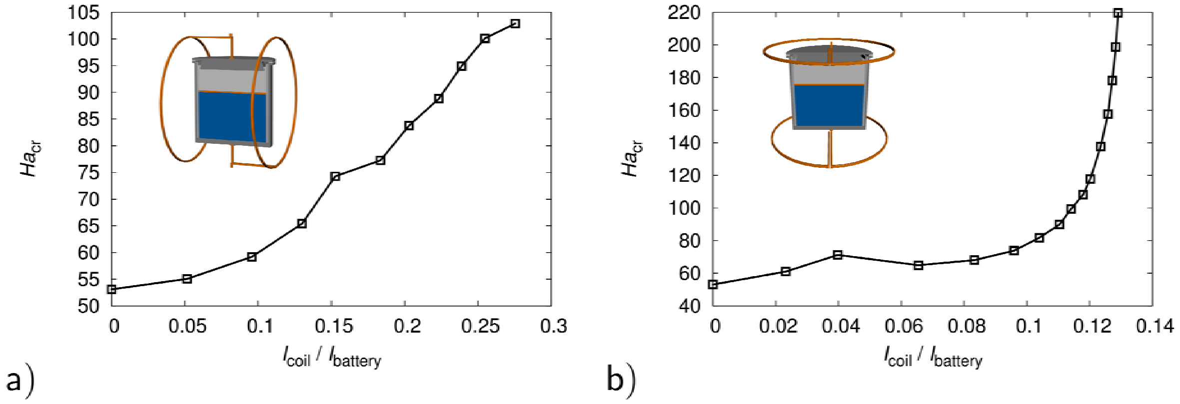

Figure 3: Critical Hartmann number for onset of the TI in a cuboid electrode of aspect ratio height / side length = 0.5 with applied horizontal a) or axial magnetic field b).

Both measures require an internal bore in the battery – which is an efficient solution for suppressing the TI, but may increase the price as the construction becomes more challenging (e.g., due to different thermal coefficients of expansion). An alternative solution is to provide an external magnetic field, generated by a Helmholtz coil [6]. Applying a purely horizontal magnetic field increases the critical current just slightly (figure 3), while an axial magnetic field suppresses the TI very effectively with guiding only 15% of the battery current through the Helmholtz coil.

Apart from the methods described above, one may also consider to guide the feeding current back on the side of the battery (figure 4). We show here results for a cylindrical electrode with aspect ratio 1 and a lateral wire at $r = 1.1R$. The current flowing through the wire is variable and may be as large as the cell current. Using this countermeasure, the cell current may be increased only by a factor of 1.7, i.e., this measure is not very effective. It should be noted that with several stacked batteries, the current through the wire may be even higher than the single cell current. In such a case, the return current may not be stabilising any more, but even trigger the TI "in opposite direction".

Providing several conductors side by side to the battery and splitting the back flowing current through all of them allows for a more homogeneous magnetic field distribution (figure 5). Especially when using two symmetric conductors, the cell current may be increased by a factor of 2.8 without triggering the TI. Using instead of this configuration three not symmetric wires, the results are similar as for a single one (figure 5b).

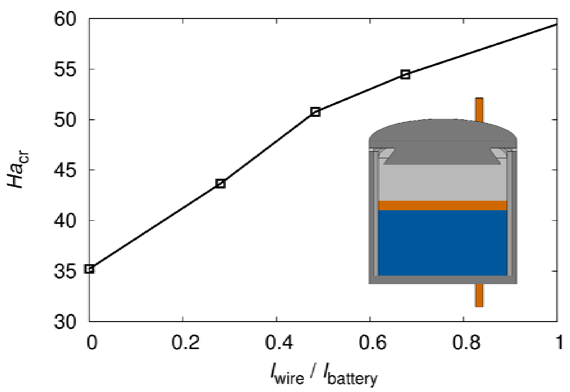

Figure 4: Simulation of the critical Hartmann number for the onset of the TI for a cylindrical electrode with aspect ratio 1. The feeding current is guided back through a wire side by side to the battery.

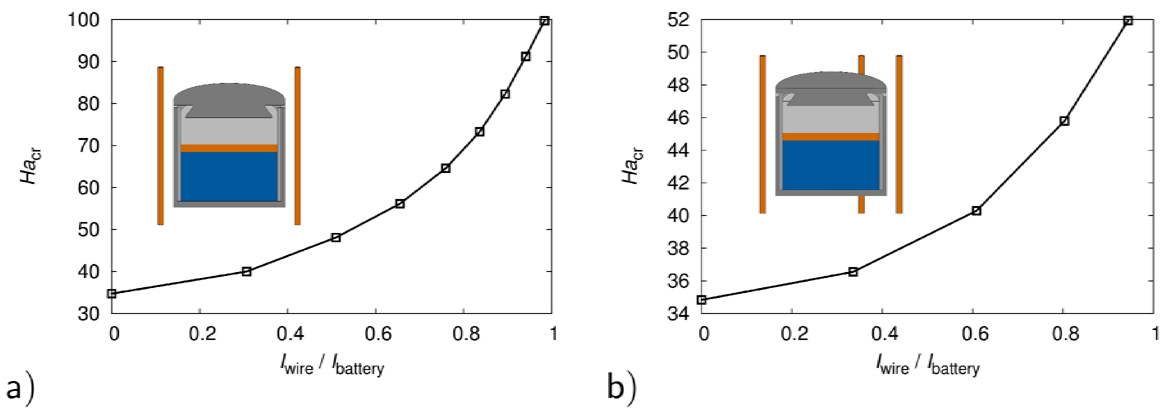

Figure 5: Simulation of the critical Hartmann number for onset of the TI for a cylindrical electrode with aspect ratio 1. The feeding current is lead back through 2 a) or 3 wires b) side by side to the battery.

5. Conclusion and outlook

We have shown that the understanding of MHD effects in LMBs is a key requirement for up scaling such batteries in order to exploit the economies of scale. We have focussed especially on the effects of the Tayler instability, which will indeed be relevant for cells with an aspect ratio larger than one with thin electrolyte layers.
The onset of the TI will take place at Hartmann numbers between 29 and 35 for an electrode aspect ratio between 0.5 and 1. While the corresponding currents may still be tolerable, Hartmann numbers in the range of 100 will induce fluid flows in the order of a few centimetres per second, which will definitely be harmful to LMBs. The consequences will be further studied with multiphase simulation.
Besides of characterising the TI in LMBs we have also proposed a number of effective countermeasures for taming the instability. In particular, providing an additional axial magnetic field generated by a Helmholtz coil is one of the most promising options for stabilising the battery. We have shown further, that an appropriate placement of the feeding lines to the battery may be used for stabilisation.

6. Acknowledgements.

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