International Workshop on Liquid Metal Battery Fluid Dynamics

LMBFD 2017

May 16-17, 2017, Dresden, Germany

Book of Abstracts

LIMTECH Alliance

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Helmholtz-Zentrum Dresden - Rossendorf

Douglas Kelley
University of Rochester

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Programme LMBFD2017

as of May 5 2017

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9:10 An overview of liquid metal batteries
*Donald Sadoway (**invited**)*

10:00 Sodium-Zinc liquid metal battery
K.S. Osen, O. Kjos, O.E. Kongstein, C. Sommerseth, A.M. Martinez, A. Solheim, A. Støre, G.M. Haarberg, J. Xu

10:30-11:00 Coffee

11:00-12:00 Electrochemistry II session chair: G. Mutschke

11:00 On the importance of ionic conduction in the molten salt confined between liquid electrodes
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11:30 Ionic mixtures with volume constraints: models and numerical approaches
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P. Personnettaz, T. Köllner, M. Nimtz, N. Weber, T. Weier

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V. Bojarevics, A. Tucs, K. Pericleous

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11:00 Coupling and stability of interfacial waves in liquid metal batteries
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11:30 MHD stability of liquid metal batteries
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14:30 Sun, batteries, sun
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15:00-15:30 Coffee

15:30-17:00 Electro-vortex flows/Advanced measurement techniques session chair: C. Nore

15:30 Small scale interface instability generated by an electro-vortical mechanism
A. Kharicha, E. Karimi-Sibaki, M. Wu, A. Ludwig

16:00 Current-driven flow in a liquid-metal-battery-like geometry
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16:30 Flowmapping in a model of a secondary hydraulic zinc-air battery
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Important information

Conference venue
QF Hotel Vienna House Dresden (address: Neumarkt 1, tel.: +49 351 563 3090) at the top floor.

Talks
Regular talks should be 20 to 25 minutes long with 10 to 5 minutes for questions. The total time including questions should not exceed 30 minutes.
Please upload your presentation to the conference notebook before the session starts.

Dinner
The conference dinner will take place on Tuesday in the restaurant *Lingnerterassen* (address: Bautzner Str. 132, tel.: +49 351 456 8510) at 19h30. For the transfer, please meet in front of the conference hotel at 19h00. There will be a transfer back to the hotel at 22h00. You can also take the tram number 11. The stops are Postplatz (city center) and Elbschlösser (restaurant).

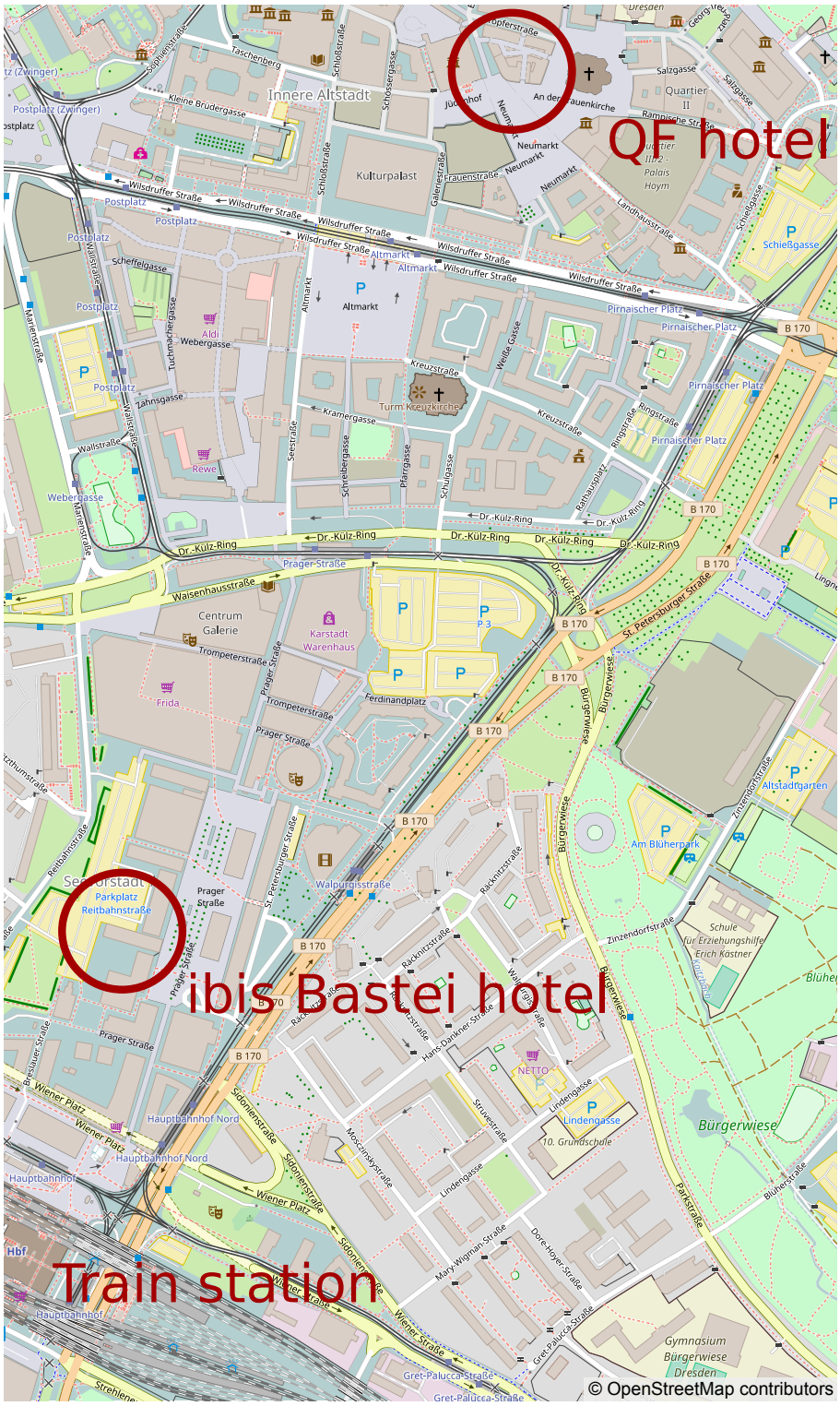
Bars & Nightlife
Coming from the conference hotel, cross the river and walk straight ahead to *Alberplatz* to the neighbourhood of *Neustadt* (25 min). There you find a variety of bars and restaurants. Recommendations: Schokoladenbar, Wohnzimmer (chocolate bars), Planwirtschaft, Café Continental (eat and drink). Vegan dishes are served at Falscher Hase & Steffenhagen.

Historic center
You find all the main sights around the conference hotel.

Public transport
You find all information on www.dvb.de.

Maps & directions

Arrival



Arriving by bus or train, please get off at Dresden Main Station *Dresden Hauptbahnhof / Dresden Hbf.* The hotel *ibis BASTEI* is within 5 min walking, the *QF Hotel* within 20 min walking distance.
Arriving at the airport you may take a taxi (ca. EUR 20) or the train. The latter leaves from the basement of the airport; there is only one line S2 which takes you directly to Dresden Hauptbahnhof. Please take care not to deboard at Dresden-Neustadt that is a larger station three stops earlier. The train leaves every 30 minutes and takes about 22 minutes. Please buy your ticket in advance at the ticket machine on the platform and stamp it before entering the train. Take a single journey ticket (called *Einzelfahrschein*) for EUR 2.30. It is valid for one hour after stamping.

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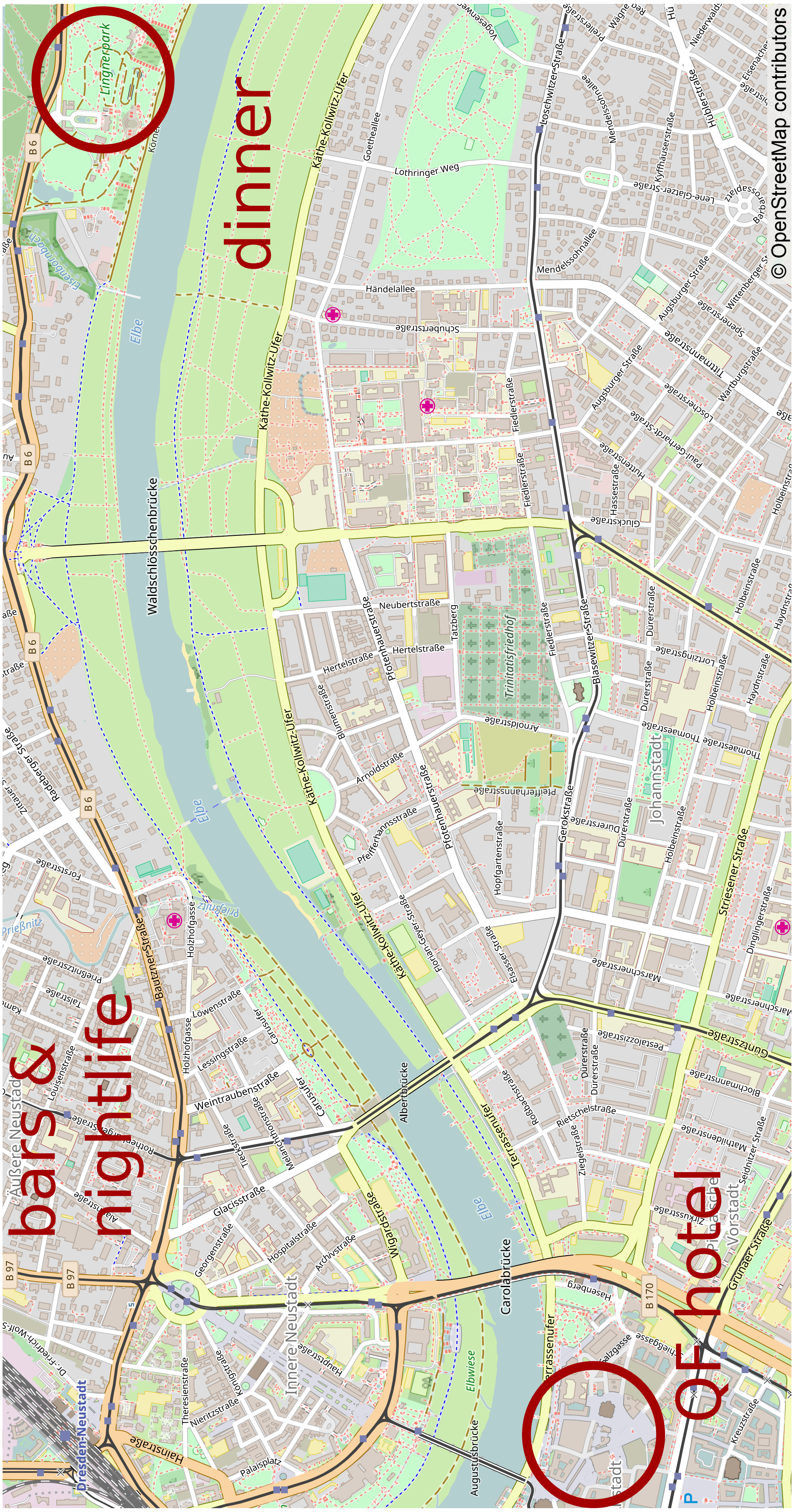
Dinner


dinner
bars &
nightlife
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Sodium-Zinc Liquid Metal Battery

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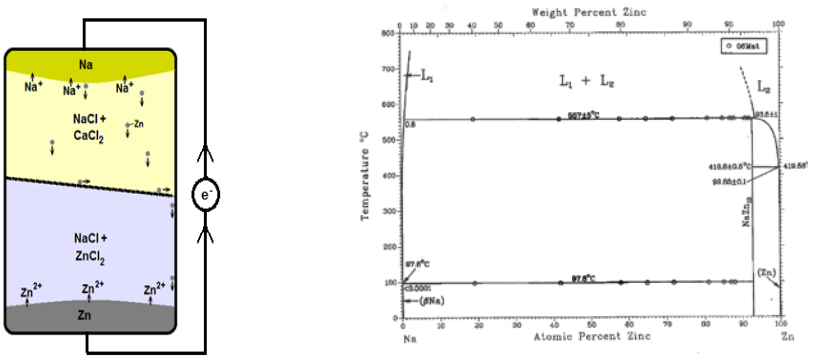
Renewable energy sources and increase of energy efficiency have been named as the most important instrument to solve the global climate challenges and secure energy supply. However, the intermittent nature of wind and solar power requires possibilities for intermediate storage to accommodate the energy production to the demand at any time. Batteries in general and liquid metal batteries in particular could offer good solutions for the integration of renewable resources and meet the performance requirements of grid-level stationary storage; they might have the right power and energy characteristics, long cycle life and low cost.

Sodium and zinc are both promising candidates for electrode materials in a liquid metal battery, due to their low cost and abundance. The objective of this work was to study the performance of a new type of membrane free zinc-sodium battery. The battery consists of three liquid layers; sodium at the top as the negative electrode, a sodium chloride based electrolyte in the middle, and zinc at the bottom as the positive electrode. To prevent the zinc containing ions that will form during charging from reacting with the sodium electrode, a porous diaphragm or separator is placed between the electrodes. The idea is to utilize the immiscibility between sodium and zinc at temperatures above 558 ºC and the relatively large density of zinc so that any zinc formed at the sodium electrode forms droplets that fall back into the zinc pool. A principal sketch of the battery as well as the phase diagram for Na and Zn are shown in Figure 1.



a b

Figure 1: a) Principal sketch of battery [1], b) phase diagram of Na and Zn [2]

The charge – discharge behavior of the battery was studied in a laboratory set-up inside a glove box. The battery was built in a graphite crucible, using alumina linings and a magnesia stabilized zirconia 20 ppi (pores per inch) diaphragm. The results showed that the self-discharge rate was somewhat high, probably caused by the high solubility of sodium in these melts and too high diffusion rate of zinc containing species through the diaphragm. A continuation of the work focuses on finding a diaphragm material that has the right properties; porous enough not give too high voltage drop, but at the same time dense enough to serve its purpose to hinder zink diffusion. It should also wet the liquid zinc droplets sufficiently.

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On the importance of ionic conduction in the molten salt confined between liquid electrodes

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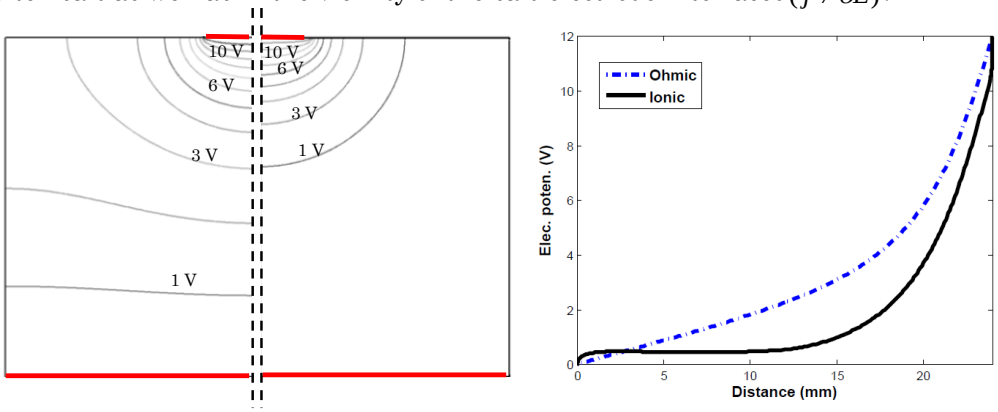
Introduction

In numerous high-temperature molten-salt-metal processes such as Liquid Metal Battery (LMB), Electroslag Remelting (ESR), and Aluminum Smelting (Hall-Heroult), the hydrodynamic behavior is strongly impacted by the electromagnetic field. Thus, an accurate prediction of the field is a crucial step toward modeling those processes. Generally, an effective electrical conductivity is considered as the diffusion coefficient for the electric potential to model the electric field although the electric current is conducted by the movement of ions in the molten salt [1, 2]. In the present study, the contribution of the ionic conduction to the electric filed in a typical molten salt composed of CaF_2 (%wt. 94)-FeO (%wt. 6) is highlighted. Here, only the ferrous ion (Fe^{2+}) participates in Faradaic reactions which occur at the metal-salt interface. Two cases are compared: (i) calculated electric potential field considering an effective electrical conductivity for the molten salt using ohm's law ($\vec{j} = \sigma \vec{E}$), (ii) calculated electric potential field considering ionic conduction in the molten salt using Poisson-Nernst-Planck (PNP) equations [3].

Results

Fig. 1 illustrates the computed electric potential field for the aforementioned case studies. The movement of ions by diffusion and electro-migration can significantly influence the field in the bulk of the molten salt as well as in the vicinity of the salt-electrode interfaces ($\vec{j} \neq \sigma \vec{E}$).



(a) (b)

Fig. 1: (a) Isolines of electric potential in the bulk and near liquid electrodes (red lines): Ohmic (left half) versus ionic (right half) conduction; (b) Variations of the electric potential along the axis are compared (V=12 V and j ~10^4 $A.m^{-2}$).

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Ionic mixtures with volume constraints: models and numerical approaches

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Approaches to the modeling of ionic mixtures based on dilute solution theory assume infinitely small ionic molar volumes and ignore solvation effects. Due to the breakdown of the dilution assumption in polarization boundary layers, in many cases, these models fail to be predictive. We report on classical [1, 2] and recent [3, 4] approaches to improve the situation by taking into account finite ion sizes and solvation via a proper notation of incompressibility, account for the chemical potential of the solvent, and relationships between chemical potential and concentrations including pressure. From this more general approach, we derive a model for ionic liquids in equilibirum which provides good qualitative coincidence with measured double layer capacitance curves.

An exponential fitting upwind finite volume scheme on Delaunay triangulations developed for charge transport in semiconductor devices is generalized to take into account the ionic interaction effects occuring in the improved models [5, 6].

We further report on the recent development of pressure robust finite element methods [7, 8] for the numerical solution of the Navier-Stokes equations. One important advantage of these methods is their ability to provide a pointwise divergence free discrete solution. Coupling with the aforementioned finite volume scheme for solute transport results in a simulation approach which provably provides discrete solutions which observe physically meaningful bounds.

Combining these recently developed methods, we report on first simulation results for electroosmotic flows in nanopores.

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Liquid metal batteries: activities at HZDR

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The talk will provide an overview of the liquid metal battery (LMB) related activities at Helmholtz-Zentrum Dresden - Rossendorf (HZDR) [1] with a focus on magnetohydrodynamic aspects of future large scale LMBs. High current densities in the range of 4 up to 130 kA/m^{-2} [2, 3], as typical for LMBs, together with cells of large cross section will result in substantial currents accompanied by considerable magnetic fields. Thus electromagnetically driven flows and instabilities should be of concern for large enough installations, especially when the thin electrolyte layers necessitated by the limited open circuit voltages are taken into account. Beneficial effects of mild electromagnetically driven flows are to be expected for the cathodes were mixing should improve cell performance.

The Tayler instability (TI) [4] can be understood as a generic case of a current driven instability under perfectly uniform current, i.e., ideal conditions. In this sense it constitutes sort of an upper bound for a current bearing fluid to remain at rest. Modifying the magnetic field distribution in the cell is an effective means to suppress the TI. Different field configurations [5, 6] to achieve TI suppression and their relative merits will be discussed and related to TI saturation mechanisms [7]. Non-uniform current distributions are more typical for real settings. They give rise to rotational Lorentz force distributions and will thereby also generate electro-vortex flows (EVFs). In terms of LMBs the concrete shape of the current collectors plays a crucial role in whether EVFs exist and how they might interact with the TI [8]. We will conclude with a discussion of electromagnetically exited interface instabilities quite similar to the sloshing modes known from aluminium reduction cells [9].

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Study of the Electrochemical and Thermal Stabilities of Different Ionic Liquids as Electrolytes for Low Temperature Liquid Metal Batteries

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Abstract

Various ionic liquids (ILs) were investigated in order to confirm their suitability as electrolytes for Li-Ga based low temperature liquid metal batteries. Special focus was given to the Li[TFSI] in [BMP][TFSI] and Li[FSI] in [BMP][FSI] ILs.

Physicochemical properties of the Li || 1(M) Li[TFSI] in [BMP][TFSI] || Ga and Li || 1(M) Li[FSI] in [BMP][FSI] || Ga cells, such as thermal and electrochemical stabilities, were investigated. Galvanostatic cycling at the current density ±4 mA cm^{-2} and operating at 220°C showed a good reversibility and stability with cycling. However a capacity fade was observed if the cell was fully discharged. On the other hand, galvanostatic intermittent titration technique was performed in order to assess the lithium ions diffusion coefficients in the above ionic liquids.

Finally a study by differential scanning calorimetry was necessary to study the thermal stability of the electrolytes at the cell operating temperatures.

Visual observation and charge/discharge behaviour of liquid metal cells

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Over the last years, several experiments on liquid metal battery (LMB) materials and different electrode and electrolyte systems were performed at HZDR [1]. The presentation will give an overview on experimental equipment and setup, preparation steps of cell and container materials and cell charge/discharge behaviour. Main focus lies on the visual observation of several chemical incompatibilities and/or mechanical processes in LMB cells and liquid metal - molten salt - container material systems.

References

[1] Stefani, F., Galindo, V., Kasprzyk, C., Landgraf, S., Seilmayer, M., Starace, M., Weber, N., Weier, T. (2016) Magnetohydrodynamic effects in liquid metal batteries. IOP Conf Ser Mater Sci Eng **143**, 012024.

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International Workshop on Liquid Metal Battery Fluid Dynamics
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Numerical studies in liquid metal Rayleigh-Bénard convection

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Liquid metal batteries (LMB) are one of the potential technological applications that involve thermal convection processes as one main ingredient. While the middle electrolyte layer, which is composed of a molten salt, will be determined by convection with internal heat sources, the liquid metal electrode at the top can be approximated by a standard Rayleigh-Bénard convection setup – a fluid layer of height H which is heated from below and cooled from above. Turbulent convection will cause a mixing of the electrode fluid and thus a enhanced transport of heat and momentum. Direct numerical simulations which resolve the fine structure of turbulence down to the smallest (Kolmogorov) scale are currently the only way to access the fully resolved three-dimensional structure of the turbulent convection flow in a liquid metal. Here, the Boussinesq equations are solved by a spectral element method with a high-order polynomial expansion of all turbulence fields on each spectral element [1, 2].

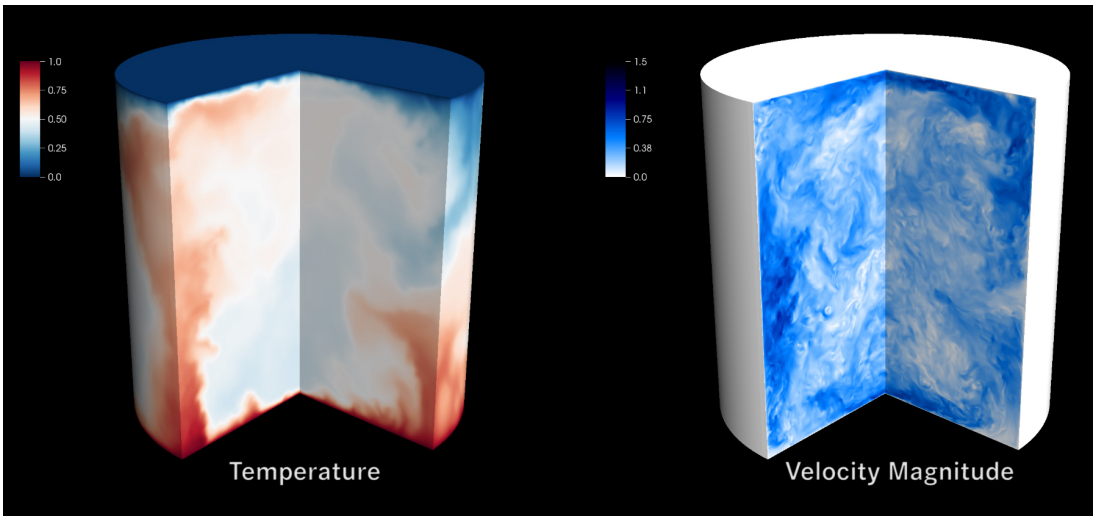

Fig. 1: Snapshot of a turbulent natural convection flow at $Ra = 10^8$ and $Pr = 0.021$. Left: temperature. Right: velocity magnitude. The aspect ratio of the cylindrical cell is $\Gamma = D/H = 1$ with D being the cell diameter.

We present studies of the global transport of heat and momentum for two series of convection flows at different Rayleigh number, convection in liquid mercury at a Prandtl number $Pr = 0.021$ and convection in liquid sodium at $Pr = 0.005$. Our analysis is focussed to the large-scale flow in the closed convection cell as well as the dynamics inside the viscous and thermal boundary layers. When the Rayleigh number is large enough, the dynamics at the bottom (top) can be separated into an impact region of downwelling (upwelling) plumes, an ejection region of upwelling (downwelling) plumes, and an interior region away from the side walls which is

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dominated by the shear of the large-scale flow (see figure 1). We find that these boundary layers are highly intermittent which might impact the mass transport across the liquid-liquid interface in a real LMB setup.

The work is supported by grant GRK 1567 of the Deutsche Forschungsgemeinschaft. Computer time is provided by INCITE project LiquidGaNa of the US Department of Energy and Large Scale Project HIL09 of the John von Neumann Institute for Computing. Computations were carried out on Blue Gene/Q Juqueen at the Jülich Supercomputing Centre (Germany) and Blue Gene/Q Mira at Argonne National Laboratory (USA).

References

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Assessment of thermal phenomena in Li||Bi liquid metal batteries through analytical and numerical models

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Thomas Köllner, Michael Nimtz, Norbert Weber, Tom Weier
Helmholtz-Zentrum Dresden - Rossendorf, Dresden, Germany

Liquid metal batteries (LMBs), built as stable density stratification of two liquid metals separated by a molten salt, are a promising electrical energy storage technology. While their operation has been proved for small prototypes, large industrial cells are not yet available. Up-scaling requires the full knowledge of the different phenomena occurring in LMBs. In this work we focus our attention on thermal phenomena, these are one of the main cause of flow inside the cell [1, 2, 3].
The system is first studied with a 0D electrochemical approach, focusing the attention on reversible and irreversible phenomena. A simple voltage model for the Li||Bi cell and the formulation of heat generation terms are proposed. From multi-physics considerations the geometrical and operating parameters are fully estimated.
Then thermal phenomena proper of LMBs are analyzed in the framework of continuum mechanics. 1D pure heat conduction models are built in order to assess the effect of different heat generation terms. Radiative heat transfer in the molten salt layer is also estimated. Finally the VOF multiphase solver `multiphaseInterFOAM` is improved in order to study thermal convection in multi-layer systems. The comparison of results of our solver to the ones of a pseudo-spectral code [3] and the first results of thermal convection in LMBs are also presented (Fig. 1) [4].

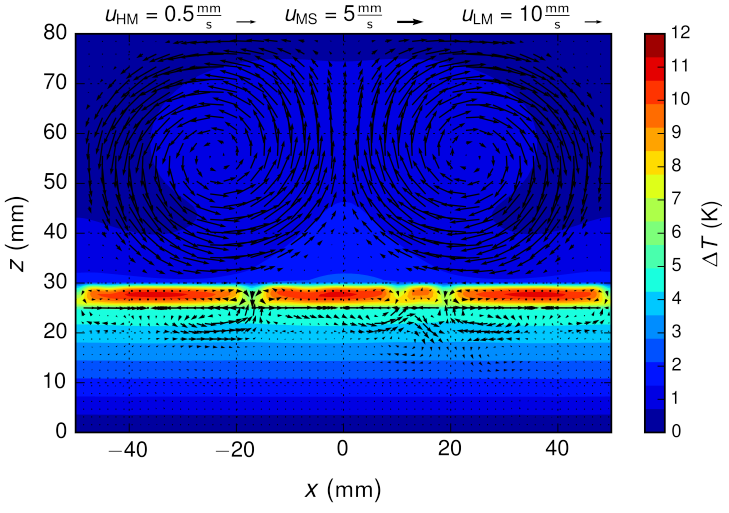

Fig. 1: Temperature and velocity distribution in a Li||Bi cell.

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Thermal Rayleigh-Marangoni convection in a liquid-metal-battery model

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The operation of a liquid metal battery (LMB) produces Ohmic losses in the electrolyte layer that separates both electrodes. As a consequence, temperature gradients will be established making the system prone to thermal convection since density and interfacial tension depend on the local temperature. The knowledge of convective transport mechanisms in LMBs is necessary for their design, e.g. preventing short-circuits and controlling the temperature. Our numerical investigations [1] follow recent studies of Shen and Zikanov [2] that considered a three-layer model consisting of a liquid metal alloy cathode, a molten salt separation layer, and a liquid metal anode at the top. Both electrodes are held at a fixed ambient temperature. The model of Shen and Zikanov [2] based on the Navier-Stokes-Boussinesq and heat transport equations, is extended by including interfacial tension gradients (the Marangoni effect) and completely accounting for all differences in the transport properties between phases.

We analyzed the linear stability of pure thermal conduction and performed three-dimensional direct-numerical simulations by a pseudospectral method, where we probed different: electrolyte layer heights, overall heights, and current densities.

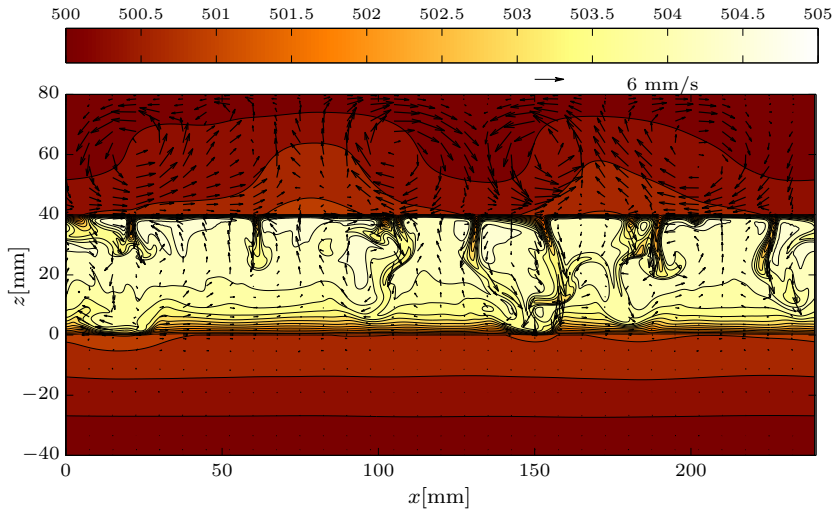

Fig. 1: Temperature distribution (color in °C) and velocity distribution of a simulated system with $3\mathrm{kA}/m^2$ current applied.

Four instability mechanisms are identified, which are partly coupled to each other: buoyant convection in the upper electrode, buoyant convection in the molten salt layer, and Marangoni

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convection at both interfaces between molten salt and electrode. A snapshot of the vertical temperature and velocity distribution, showing typical convective motion, is displayed in Fig. 1.

The linear stability analysis confirms that the additional Marangoni effect increases the growth rates of the linearly unstable modes, i.e., Marangoni and Rayleigh-Bénard instability act together in the molten salt layer. The critical Grashof and Marangoni numbers (based on the bottom electrode properties) decrease with increasing middle layer thickness. The calculated thresholds for the onset of convection are found to appear at practical current densities of laboratory-sized LMBs. The global turbulent heat transfer follows scaling predictions for internally heated buoyant convection. In summary, our studies show that incorporating Marangoni effects generates smaller flow structures, alters the velocity magnitudes, and enhances the turbulent heat transfer across the triple-layer configuration.

Financial support by the Deutsche Forschungsgemeinschaft in the framework of the Priority Programme SPP1506 is gratefully acknowledged. Furthermore, we thank the Computing Centre (UniRZ) of TU Ilmenau for access to its parallel computing resources.

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Investigation of instabilities of a liquid metal/electrolyte interface caused by thermal convection.

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Introduction

We report about a two-fluid experiment where the behavior of a liquid metal/electrolyte interface is studied. This experiment is a simplified model of a liquid metal battery (LMB) which is a promising device with regard to energy storage and grid stabilization [1]. LMBs generally consist of two liquid metal layers and an electrolyte layer which lies between them. Because hydrodynamic stable interfaces are a key factor for the operation of a LMB, interface deflections caused by thermal convection were investigated. In a LMB there are two reasons for the onset of thermal convection. One is heating of the walls to maintain the necessary operational temperature and the other is Joule heating in the electrolyte [2, 3]. The experiment contains Ga-In-Sn-alloy (Galinstan) as the lower phase and an electrolyte as the upper phase. This two-layer cell is heated from the bottom and cooled from above and represents in principle a Rayleigh-Bénard cell. To measure velocity profiles we apply Ultrasonic Doppler Velocimetry (UDV) for the liquid metal and optical measurement techniques like Particle Image Velocimetry (PIV) for the electrolyte. A Laser triangulation sensor is used to scan the interface and to measure the deflection caused by thermal convection. The echo of an UDV probe is used for comparison. Measurement results will be presented to give a first estimate whether the interface deflection may impair the operation of a LMB negatively.

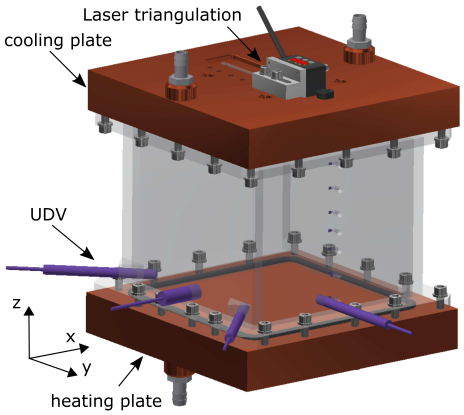

Fig. 1: Two-fluid convection cell with Galinstan as the lower layer and an electrolyte as the upper layer.

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Magnetically stabilised large scale liquid metal batteries

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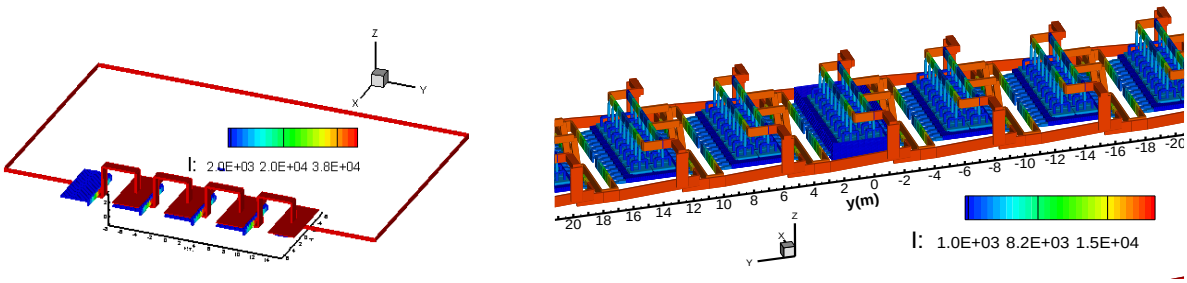
Introduction

One of the risk factors in designing liquid metal batteries is their operation sensitivity to liquid motion (caused mainly by electromagnetic forces), which potentially may lead to the top and bottom liquid electrode short-circuiting, accompanied by electrochemical and thermal problems. A very similar destabilization mechanism is observed in Hall-Héroult cells, where the liquid aluminium and electrolyte thicknesses are carefully adjusted and controlled for stable and efficient technological process [1,2]. In the case of liquid metal batteries the maximum thickness of the electrolyte layer is limited by the requirement that the voltage loss in the electrolyte must not exceed a significant portion of the available thermodynamic driving force (open circuit voltage). For these conditions, a careful stability analysis of the liquid interfaces becomes imperative.

Results

The previously validated MHD model [1,2] after some adjustment to the 3-layer structure of the large scale liquid metal batteries demonstrates that it is possible to design a stable to dynamic perturbation operating cell if using the optimized bus bar configuration. The bottom heavier metal layer is very stable to perturbations, leaving the top lighter metal (Mg, Li, Ca) interface stability as the critical step to control. The flow velocities and the interface dynamics are analysed for two comparison cells of large horizontal extension (8 m) and relatively small depth of the liquids (2 – 10 cm). The comparison of a simple cell (left in the Figure) and the magnetically optimised cell (right), based on the Trimet Hall-Héroult cell [2], shows that from the MHD point of view a practically suitable facility could be created based on the already available design principles.



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Metal pad roll in cylinders : perturbation theory vs. DNS

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Introduction

Liquid metal batteries (LMBs) structurally have much in common with electrolysis cells that are used in the Al-industry and therefore it can be expected that they are prone to similar magneto-hydrodynamical instabilities. Metal pad rolling is one of many instabilities that is currently in the spotlight (see[1, 2, 3, 4] for recent work in LMB context).

The physical origin of this metal pad roll instability in reduction cells is well described in a furnished literature that goes back to the 70's. Most theoretical insights have however been found within the restrictive context of quite a number of supplementary assumptions (shallow layers, inviscid, magneto-static, negligible terms in Lorentz force). In lab-scale devices, such as that of [5, 6], fluid layers are however not necessarily shallow and the set-up is also small enough for viscous dissipation to become important. Finally, also the magnetic dissipation cannot be ignored given that stronger magnetic fields are necessary to trigger the instability. A critical comparison between theory and experiments or direct numerical simulation (DNS) dedicated to lab-scale devices requires a more detailed stability model.

In this talk, I present a theoretical stability analysis dedicated to cylindrical reduction cells (2 layers). Using a perturbative approach we find explicit formula for the growth rate of the metal pad roll instability and without making the most common assumptions. We deal with fluid layers of arbitrary heights and incorporate both magnetic and viscous damping effects. We confront our theory to direct numerical simulations (DNS) that are done with two different multiphase MHD solvers (SFEMaNS and OpenFOAM). This comparison also allows us to measure what precision really is required to obtain converged three-dimensional numerical simulations.

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Stability of fluid layers carrying a normal electric current revisited

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The recently-invented liquid metal batteries (LMB) offer an economic storage for the fluctuating power supply from wind turbines and other renewable sources. The LMB comprises two layers of molten metal separated by a thin layer of electrolyte which should be able to convey strong electric currents. The attraction of parallel currents passing through the battery during its charge/discharge cycles gives rise to an electromagnetic pinch force which may be balanced by the hydrodynamic pressure gradient provided that the current density is sufficiently low and uniform. This balance may become unstable if the current exceeds a certain critical threshold which depends on the design of the battery. The flow of molten metal ensuing from the instability may disrupt the electrolyte layer and thus cause the failure of the battery.

The aim of this presentation is to clarify the basic features of electromagnetic interfacial pinch-type instability by revisiting the elementary model introduced by Sneyd [*J. Fluid Mech.* 156, 223, 1985] for aluminum electrolyzers. The model consists of horizontally unbounded fluid layers carrying a uniform normal current in the presence of a co-planar vertically invariant magnetic field.

We show that the electromagnetic force resulting from the interaction of the electric current with own magnetic field has no effect on the interface between two layers which are vertically unbounded. It means that besides the conductivity difference, additional asymmetry between two layers is required for the electromagnetic effect on the interface to arise. In a two-layer system, such an asymmetry occurs when part of the electric current associated with the interface perturbation closes through a solid electrode. This effect can destabilize the interface between a finite-depth layer bounded by a solid electrode and a vertically unbounded layer when the latter has a lower electrical conductivity than the former. In contrast to the channel of finite width considered previously, the effect in laterally unbounded system vanishes when the electrode is poorly conducting relative to the bounding liquid. For the liquid metal batteries with the middle layer made of an electrolyte with a lower electric conductivity than the top and bottom metal layers, our results suggest that the electromagnetic force has a stabilizing effect. Extension of our results to a mirror symmetric three-layer system shows that the electromagnetic force has a much stronger stabilizing effect on the pinch-type disturbances than on the kink-type disturbances.

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Shallow-water modeling of metal pad instabilities

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A shallow-water model of melt flows and electromagnetic effects in liquid metal batteries is derived and applied to analyze the metal-pad instability in a wide range of parameters. Two types of the instability are detected. One is a generalization of the instability known for the aluminum reduction cells. Another is a new 'overturning' instability related to the interactions of current perturbations with the azimuthal magnetic field induced by the base current.

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Coupling and stability of interfacial waves in Liquid Metal Batteries

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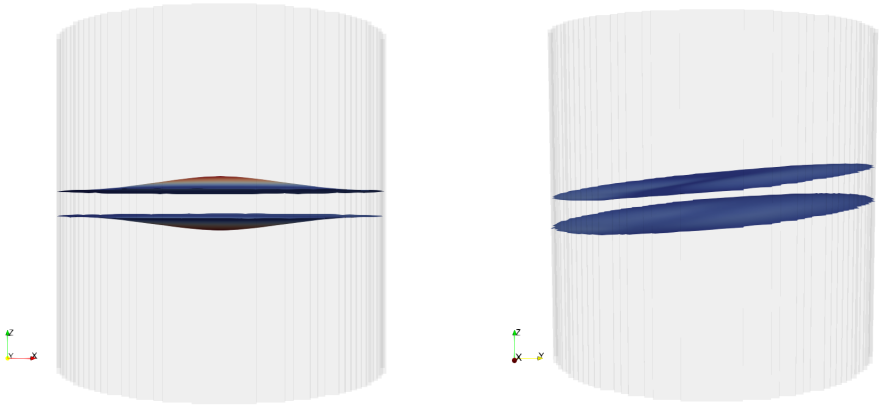
Introduction

Liquid metal batteries (LMBs) are expected to be highly susceptible to various kinds of magneto-hydrodynamical instabilities due to their similarity with aluminium reduction cells. In particular the metal pad roll instability, which may be induced by interactions of horizontal compensations currents with an external vertical magnetic field, was identified as a key instability mechanism capable to cause short-circuits in LMBs [1, 2, 3]. The stability threshold can be roughly predicted by exploiting two-layer stability criteria originally developed for reduction cells [1]. However, in LMBs an additional interface is present that may strongly influence the global stability depending on many parameters. Both interfaces are closely coupled for shallow salt-layers such that both interfaces may excite each other and can be coupled by different oscillating modes having different consequences for operation. Further, it is not clear so far which interface will be excited first and which interface will experience a stronger influence of the magneto-hydrodynamical forces.

To get deeper insights into the coupling behavior gravity-capillary waves in generic cylindrical containers were studied analytically using potential theory. A dispersion relation containing two-different coupling modes was derived. Further, the global coupling could be described by only two dimensionless parameters. On this basis, a coupling criterion is suggested predicting for which parameter regimes both interfaces can be considered as to be fully decoupled such that two-layer stability analysis becomes sufficient.

In addition, numerical studies were conducted for validation. For highly coupled cases two different kinds of instabilities were discovered. One of them probably involves some new physical aspects and cannot be explained by the metal pad roll instability mechanism alone.

Results



(a) (b)

Fig. 1: Two different types of instability observed for perfectly coupled interface waves with the same eigen-frequencies. (a) radial-symmetrically counter-rotating waves present over a high range of cell currents. This dynamic may also be associated with the overturning instability. (b) Metal pad roll-like waves that are rotating in phase present only for higher cell currents. This dynamic cannot be really explained by the metal pad roll instability, since the compensation current is occurring mainly in the salt layer and not in the metal layers.

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MHD stability of liquid metal batteries

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Introduction

Liquid Metal Batteries have many important characteristics for efficient use in combination with intermittent renewable energy sources on a national energy grid scale [1]. The concept of liquid batteries bears a close similarity to aluminium electrolytic production cells. The aim of this research is to develop a stability theory for three density-stratified electrically conductive liquid layers using 3d and shallow layer approximations taking into account the coupling between interface waves and the electric current redistribution during periods of battery charge/discharge [2].

Results

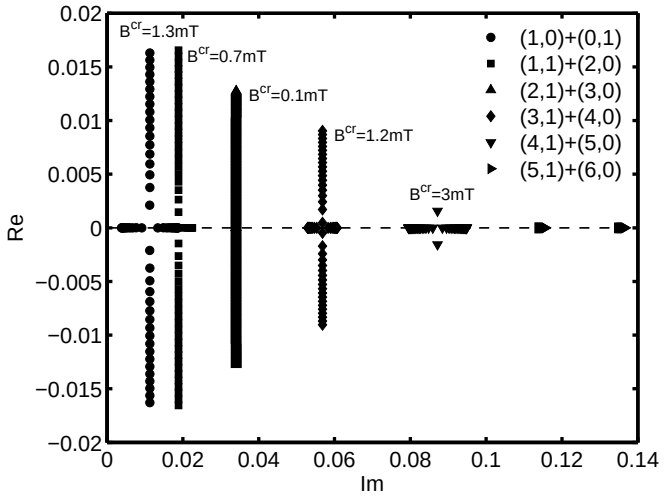

Fig. 1: Eigenvalue analysis for upper interface, magnetic field impact ($B_z = B_{0z} + N\Delta B$, where $0 \leq B_z \leq 3mT$, $\Delta B = 0.1mT$).

Numerical stability criteria for the cases of practical interest are compared for different interfacial mode interactions in the two and three layer approximation. We show that the two layer approach based on consideration of the interface between the upper metal and electrolyte is sufficient for instability threshold prediction. Corrections for the analytical stability criteria accounting for the wave dissipation coefficients are obtained and verified with numerical solutions.

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Current path and electrode mixing: Experiments and models

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Because liquid metal batteries support currents reaching tens or hundreds of amperes, electromagnetic forces substantially affect flow inside the batteries. The paths of those currents before they enter and after they leave the battery determine internal magnetic fields. The geometry of entry and exit points sets the boundary conditions for internal current density. Careful design of current path may provide engineering advantages, for example eliminating the Tayler instability [1, 2], changing the resulting electro-vortex flow [3], minimizing surface instabilities [4], or improving mixing within electrodes and electrolyte [5].

I will talk about my team's work studying external current paths, current entry and exit, and how changing them can affect flow within batteries. Our simple numerical experiments suggest that changing the current collector size can reduce or increase mixing within an electrode, primarily because concentrated current creates heat to drive thermal convection, as shown in Fig. 1a–b. Our laboratory experiments [6], in which we measure liquid metal flow using ultrasound, show a rich array of behaviors; two examples are shown in Fig. 1c–d. To simplify the data, to characterize global flow topology using a limited set of local measurements, and ultimately to construct low-dimensional models, we project our measurements onto an appropriate set of basis modes. Two such functions are shown in Fig. 1e–f. Accurately distinguishing basis modes, however, requires careful probe placement; I will discuss our strategy. I will conclude with discussion of future work, noting other factors possibly important for battery design.

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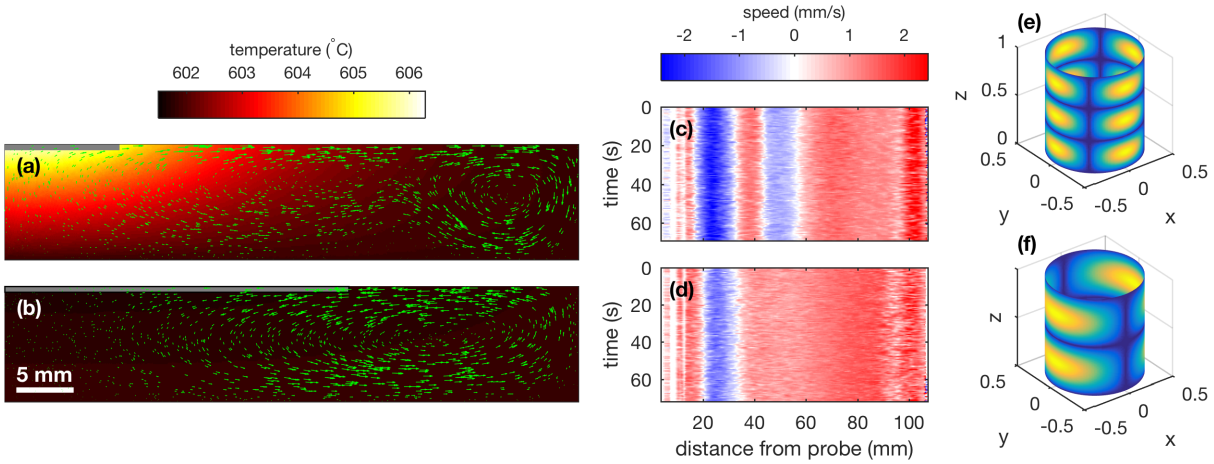

Fig. 1: (a–b), Simple simulations support the hypothesis that different current paths drive different mixing. In a axisymmetric finite element simulation of calcium alloying into bismuth, a current collector with diameter 10 mm (a) drives better mixing than a 30 mm current collector (b) because thermal convection is more vigorous. Temperature is indicated in color and velocity is indicated with arrows. (c–d), Experimental measurements of different flows caused by different current collector diameters: 25 mm (c) and 19 mm (d). (e–f), Examples of basis modes useful for constructing low-dimensional models from experimental measurements: ψ_1^{2c3} (e) and ψ_3^{1c2} (f). Each mode ψ_k^{lm} is characterized by a set of three wave numbers (k, l, m) which apply to the radial, azimuthal, and axial directions, respectively. The modes are defined throughout space, but plotted only on a cylinder for simplicity. Yellow indicates large magnitude, and blue indicates small magnitude.

Numerical simulations of incompressible multiphase hydrodynamic and magnetohydrodynamic flows

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March 1, 2017

1 Introduction

We have been developing, testing and validating a magnetohydrodynamic (MHD) code called SFEMaNS since 2002, see e.g. [1]. This code couples the incompressible Navier-Stokes equations and the Maxwell equations. It is formulated in cylindrical coordinates and uses a hybrid spatial discretization combining Fourier expansions in the azimuthal direction and finite elements in the meridian plane. We will present new developments implemented in SFEMaNS to simulate multiphase MHD flows. A time stepping technique using the momentum as dependent variable is introduced. A level set method is applied to reconstruct the fluid properties such as the density, the dynamic viscosity and the electrical conductivity. A stabilization method and a compression technique to limit the flattening of the level set function are used. Results on standard benchmark problems such as Newton's bucket problem and rising bubbles with surface tension are provided. A numerical simulation of a phenomenon related to the industrial production of Aluminium is also presented.

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2 MHD results

We numerically simulate the metal pad roll instability which can sometimes be observed in Hall-Héroult cells in Aluminium production facilities. This two-phase magnetohydrodynamic instability drives a rotating gravity wave.

The set up consists of a cylinder filled with two immiscible fluids whose electrical conductivities differ by two to three orders of magnitude. The two fluids are traversed by a vertical electrical current and immersed into a vertical magnetic field as in [2]. We show that, at a fixed vertical current, if the magnitude of the ambient magnetic field is large enough, the interface undergoes a rotating-tilting motion, as shown in figure 1.

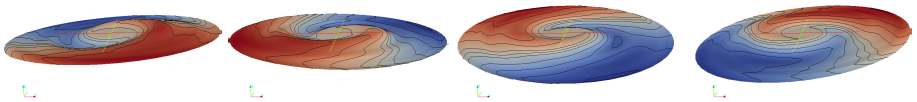

Figure 1: Snapshots of the interface's height between the two fluids at different times viewed in perspective. Computations done with a vertical current $J = 2 \times 10^4\ A/m^2$ and a vertical ambient field $B_z = 160\,Gauss$. The crest rotates clockwise as expected since $JB_z > 0$ (see [3]).

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Sun - Batteries - Sun

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Liquid metal batteries (LMBs) are presently discussed as cheap means for the storage of wind and solar energy [1]. Among other drivers of undesired fluid motion that could destroy the three-fluids stratification, the Tayler instability (TI) sets some upper limit for the upscalability of LMBs [2]. We present the principles of the TI, its possible effects on LMBs, and some simple ways to suppress it [3]. We focus on the peculiar saturation mechanism of the TI at low magnetic Prandtl numbers, which relies on the change of the hydrodynamic base state. We discuss the recently found helicity oscillations of the m=1 velocity field of the TI [4] which, in turn, might have consequences for stellar dynamo models for which the TI had originally been discussed. We show that these helicity oscillations can be resonantly excited by certain m=2 perturbations which would result, e.g., from planetary tidal forces. It is this high sensitivity of the helicity oscillations that could empower those very weak tidal forces to synchronize the entire solar dynamo [5].

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SMALL SCALE INTERFACE INSTABILITY GENERATED BY AN ELECTRO-VORTICAL MECHANISM

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Introduction

The present work aims to study the small scale coupling between Magnetohydrodynamics and multiphase phenomena during and multiphase phenomena during the aluminium reduction process. During this process strong current passes through superposed layer of electrolyte and a layer of metal. To achieve a better understanding of this coupling, a Multiphase-Magneto-hydrodynamic model was built using a potential formulation. Several simulations show surprising effects, i.e. if the imposed current reaches a certain magnitude, a liquid metal jet is formed which ejects droplets towards the upper anode. Simulations were performed in 2D and in 3D.

Results

When the applied current is sufficiently high, the wavy movement at the interface can become strong enough to generate a jet. The electro-vortex together with the magnetic pressure, have enough power to squeeze the central part of the liquid metal until break-up. The ejected droplet could splash the anode, if the bath height is too small. We propose that the known "MHD noise" and the "anode splashing" are both related to the excitation of small scale waves, which under some circumstances lead to the formation jets at the metal/bath interface.

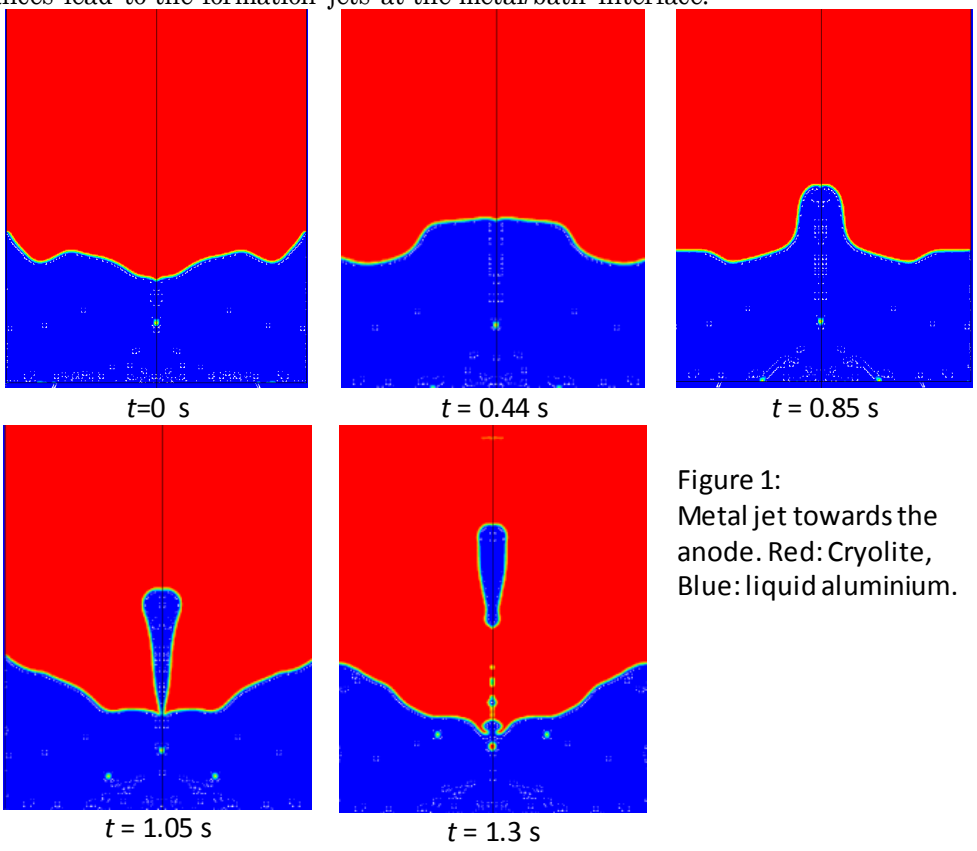

Figure 1:
Metal jet towards the anode. Red: Cryolite, Blue: liquid aluminium.

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Current-Driven Flow in a Liquid-Metal-Battery-Like Geometry

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Introduction

Fluid flow can be both a boon and a curse for liquid metal batteries. One one hand, it may promote mixing of the anode metal into the cathode, preventing it from lingering on the electrolyte-cathode interface. On the other hand, it could momentarily displace part of the electrolyte layer and thus cause a short circuit. The experiment presented here consists of a cylindrical container filled with GaInSn bounded by copper current collectors on the top and bottom, which are attached a power supply unit. The current collector is electrically insulated except for a circular surface whose area is 100 times smaller than that of the bottom current collector. This geometry emulates that of a battery whose cathode consists of a liquid metal drop attached to the top current collector dipped into the electrolyte layer while the anode extends throughout the bottom part of the container. An ultrasound Doppler array was used to perform velocimetry measurements of the electro-vortex flow perpendicularly to the cylindrical axis.

Results

While currents ranging from 10 A to 60 A are supplied to the system, the flow pattern consists of multiple stationary swirls. Additional UDV measurements that are parallel to the cylindrical axis will be performed to obtain a better understanding of the flow structure. Moreover, numerical simulations of this geometry will be carried out.

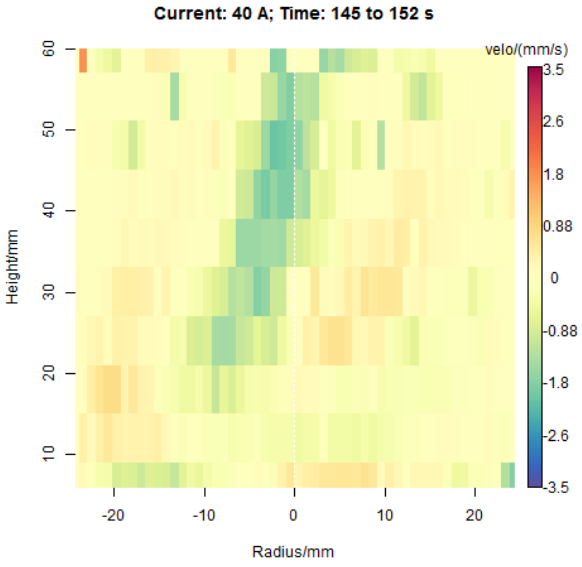

Fig. 1: Velocity profile of the electro-vortex experiment while 40 A are flowing through it. The ultrasound transducers in the array are arranged along the height of the cylinder and measure the radial component of the velocity within one plane.

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Flowmapping in a model of a secondary hydraulic zinc-air battery

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Introduction

While not employing liquid metals but a suspension of metal microparticles, secondary hydraulic zinc-air batteries are facing similar challenges concerning flowmapping to validate models for computational fluid dynamics (CFD) as liquid metal batteries. Secondary hydraulic zinc-air batteries, here referred to as zinc-air fuel cells (ZAFCs) are operated by pumping a suspension of zinc particles and an aqueous potassium hydroxide solution through an electrochemical cell. The achieved power densities depend on the electrically contacted zinc surface area, thus on the number of particles contacting the anode current collector. Therefore, the flow field in the anodic channel is a crucial influence for maximizing the power density and utilization of ZAFCs. The electrolyte suspension is a non-Newtonian multiphase fluid for which there are no reliable and validated CFD-models. Thus, in order to improve the performance of the ZAFC, experimental validation is necessary. Since the suspension is opaque due to the high particle concentration optical flow mapping is not an option. However, with ultrasound flow mapping it is possible to measure in opaque liquids as gallium-indium-tin with a sufficient penetration depth and resolution [1].
A scaled up model of the anode channel of a ZAFC is shown in Figure 1 with an L-shaped flow channel and a gap width of 15 mm. To analyse the flow profile between the mockup electrodes the spatial resolution should be at least 1.5 mm. Increasing the spatial resolution is conventionally done by increasing the ultrasound frequency and using smaller ultrasound elements. This approach is not possible for the ZAFC, since the electrolyte is a suspension of solid particles with a high volume concentration and attenuation of sound strongly increases with increasing frequency. In contrast, by using the ultrasound phased array principle the ultrasound frequency can be low while still achieving the required spatial resolution. This also allows to electronically shift the focal position in the measurement region to perform 2D measurements.

Results

We present a measurement of the 2D flow field inside a model of a ZAFC. The measurement setup is depicted in figure 1. An ultrasound phased array probe is attached to the bottom of the ZAFC model. In the desired measurement region of 15×15 mm^2 in the x-z-plane a spatial resolution of 1.5 mm is achieved through the phased array principle. The electrolyte suspension was acoustically characterized to firstly determine the speed of sound which is necessary to calculate the time delays for the phased array focusing and secondly to determine the attenuation to define the appropriate ultrasound center frequency. The flow measurements as well as the acoustic characterization were carried out with a custom modular research platform, the phased array ultrasound Doppler velocimeter (PAUDV) [2]. The measured 2D flowfield can be used to validate new numerical modelling methods for suspensions, like the Computational Fluid Dynamics/Discrete Element Method (CFD/DEM) model.

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References

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[2] Nauber, Richard and Beyer, Hannes and Mäder, Kevin and Kupsch, Christian and Thieme, Norman and Büttner, Lars and Czarske, Jürgen (2016) Modular ultrasound velocimeter for adaptive flow mapping in liquid metals. Ultrasonics Symposium (IUS), 2016 IEEE International, 1–4.

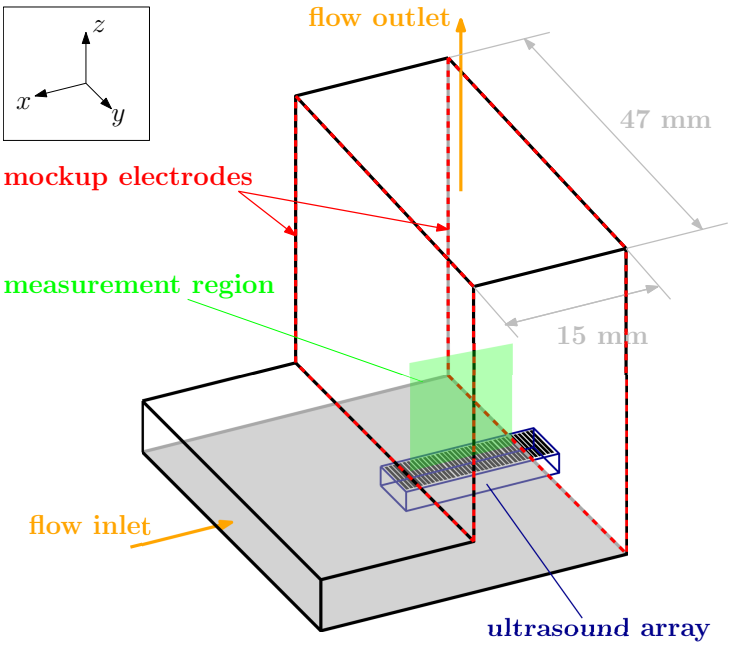

Fig. 1: Measurement Setup at the ZAFC model. The 2D1C flow field between the mockup electrodes is measured.