Technical Article

Magnetic control of fluid flows – hot topics in magneto-fluid-dynamics

***Abstract* — Electromagnetic processing of materials is an important branch of magnetofluiddynamics. An interdisciplinary research group at the Ilmenau University of Technology has investigated several aspects of the influence of magnetic fields on electrical conducting fluids (liquid metal, glass melt). There was studied the braking effect of strong inhomogeneous magnetic fields on turbulent liquid metal flows, the molding and controlling of free surfaces of liquid metals, electromagnetic stirring of glass melts and the identification of liquid metal interface motions by means of a magnetic field tomography technique. All these issues have been studied both experimentally and numerically.**

I. Introduction

Magnetofluiddynamics (MFD) or magnetohydrodynamics (MHD) is the academic discipline which studies the dynamics of electrically conducting fluids. Examples of such fluids include plasmas, liquid metals, and salt water. The word *magnetofluiddynamics* is derived from *magneto-* meaning magnetic field, and *fluid-* meaning liquid, and -dynamics meaning movement. The field of MHD was initiated by Hannes Alfvén, for which he received the Nobel Prize in Physics in 1970 [1].

The idea of MFD is that magnetic fields can induce currents in a moving conductive fluid, which create forces on the fluid, and also change the magnetic field itself. The set of equations which describe MFD are a combination of the Navier-Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism. Because these differential equations are coupled they have to be solved simultaneously.

In the year 2001 a research group was established at the Ilmenau University of Technology. It was devoted to study several basic subjects of MFD. This has been, in particular, the investigation of force and heating effects of electromagnetic fields on electrically conducting fluids. Even if MFD is also pursued in astrophysics, plasma physics and dynamics, in this case interdisciplinary research teams started to develop new environmentally friendly technologies using forces and heating effects of electromagnetic fields for the electro-magnetic processing of materials. With respect to those industrial applications where knowledge of the flow rates is required, some processes have been examined in which electromagnetic forces operate on aggressive melts such as liquid metal or molten glass.

Although nowadays melts can already be mixed, impurities removed, and droplets levitated above their crucible with the aid of electromagnetic forces, comprehensive industrial use of the possibilities is still being prevented by the absence of knowledge about many of the physical principles operating. Thus, the key aspects of activity of the research group are the prediction of the deceleration effect of strong inhomogeneous magnetic fields, the implementation of a electromagnetic plug, electromagnetic stirring of glass melts, and the contact-free measurement and detection of the position of large scale fluid-fluid-interfaces applying magnetic field tomography techniques. The goal of the research group is to achieve solutions for these highly-complex problems by a carefully designed strategy coupling high-precision experiments with high quality analytical investigations and numerical simulations.

Furthermore, there was associated a Junior Research Group "Electromagnetic Processing of Materials (EPM)" investigating electromagnetic influences on materials caused by strong magnetic fields. The group's task is to install and design the technical equipment, to produce materials due to its laboratory purpose and to measure its properties. The main objective is the controlling of the process of crystallisation of glasses and glass melts in strong magnetic fields.

II. Physical MFD Problems

The MFD research group started with the clarification of a set of, at that moment, open MFD problems:

- Prediction of the braking effect of a strongly inhomogeneous magnetic field
- Realization of an electromagnetic plug
- Electromagnetic stirring of glass melts
- Contactless identification of fluid-fluid-interface deformations

The general challenge for this interdisciplinary research team was to achieve solutions for these highly-complex problems by means of a carefully designed strategy based on coupling high-precision experiments with high quality analytical investigations and/or numerical simulations. In all projects significant progress could be achieved leading to following main scientific results:

- Clarification of the braking effect of “magnetic obstacles” (strongly inhomogeneous magnetic field)
- Comprehensive analysis of liquid metal surface instabilities affected by AC magnetic fields
- First feasibility proof of electromagnetic stirring of glass melts
- Development of a magnetic field tomography system for the identification of fluid-fluid interface deformations

In the following chapters the studied MFD problems will be described in details.

III. Electromagnetic Braking of Turbulent Fluid Flow

The presented experimental study is relevant to electromagnetic braking - a magnetohydrodynamic problem that takes place in the industrial process of the continuous casting of steel. Electromagnetic braking consists of applying a steady (DC) magnetic field to the mold in a continuous steel casting facility with the goal to improve quality of the final product. Due to Joule dissipation the magnetic field smoothes the jets of the molten steel emerging from the so-called submerged entry nozzle and suppresses undesired velocity fluctuations. Those braking effects reduce contamination of foreign particles and gas bubbles in the mold.

The problem of electromagnetic brake was investigated with respect to two general aspects:

1. Experimental investigation of the influence of an inhomogeneous magnetic field on the spatial distribution of the mean and fluctuating velocity and electric potential in a liquid metal flow.

2. Adaptation of the existing methods for potential velocimetry to the case of strongly inhomogeneous magnetic field and further development of the advanced method of Ultrasonic Doppler Velocimetry (UDV) to applications in liquid metals.

The experimental results have been used for verification of numerical simulation. In its turn the numerical simulation was supposed to provide those flow quantities which cannot be obtained by direct measurements in the experimental practice, namely: electrical current, electromagnetic force, component of velocity parallel to magnetic field and pressure distribution.
The majority of experimental results were obtained in the liquid metal loop (filled with liquid metal GaInSn) shown in Fig.1. A horizontal Plexiglass channel with 500 mm length, 100 mm width and 20 mm depth was used as a test section. Design of the experimental loop, test section, configuration of magnetic field and parameters of the experiment are described in [2].

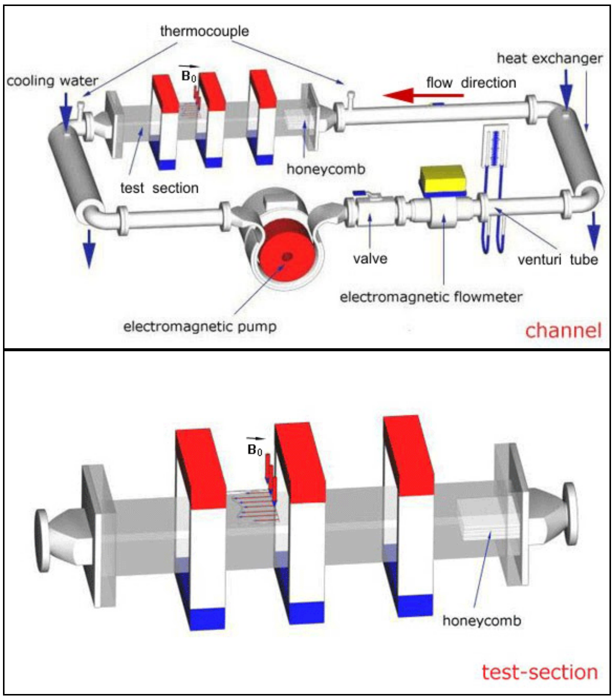


Fig 1. Experimental liquid metal loop (*top*), test section (*bottom*)

A. The H-Trough

Motivated by a newly established collaboration with the company Moeller GmbH (Bonn, Germany) there have been performed theoretical and experimental studies of the behavior of a liquid metal under the influence of an external electric current. The original motivation of this work came from application of the pinch effect in electrical engineering. However, the physics of this phenomenon turned out to be so interesting that a careful investigation of this flow in a geometry which is called "H-trough" was done [3, 4].
The experimental, analytical and numerical investigations of the behaviour of a liquid metal sheet with a free surface, called "H-trough", led to a comprehensive understanding of the instabilities and bifurcations. Moreover, the analytical model developed in frame of this work package has later been used by an industrial partner for design studies and optimization of electric current limiters.

B. Transition between 2D and 3D MHD Turbulence

A combination of linear stability analysis and direct numerical simulations was used to analyse three problems, namely the flow in the interior of a triaxial ellipsoid, and two unbounded flows, a vortex with elliptical streamlines and a vortex sheet parallel to the magnetic field. The flow in a triaxial ellipsoid was found to present an exact analytical model which demonstrates both the existence of inviscid unstable three-dimensional modes and the stabilising role of the magnetic field. Using the second model it was demonstrated, that motion perpendicular to the magnetic field with elliptical streamlines becomes unstable with respect to the elliptical instability once the velocity has reached a critical magnitude whose value tends to zero as the eccentricity of the streamlines becomes large. Furthermore, the third model indicates that vortex sheets parallel to the magnetic field, which are unstable for any velocity and any magnetic field, emit eddies with vortices perpendicular to the magnetic field [5]. Whether the investigated instabilities persist in the presence of small but finite viscosity, in which case two-dimensional turbulence would represent a singular state of MHD flows, remains an open question.

C. Flow Around “Magnetic Obstacles”

In this experiment we investigated the liquid metal flow in a situation when the magnet does not completely occupy the channel width (Fig. 2).

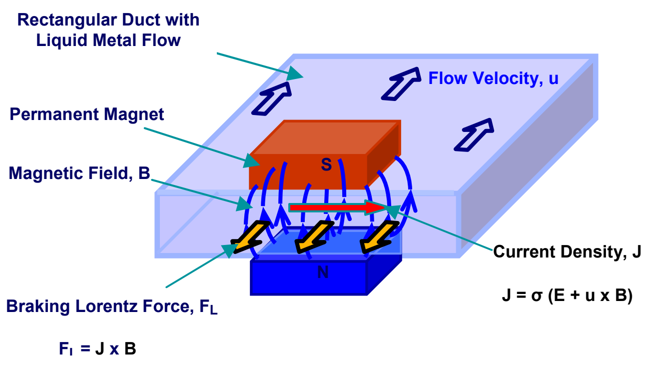


Fig. 2. Basic principle of “magnetic obstacle” acting on conducting fluid flow

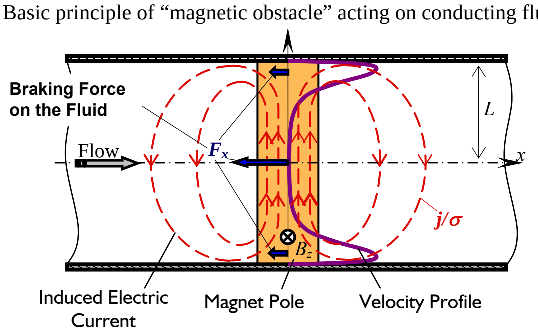


Fig. 3. Braking force caused by the permanent magnet acting on the fluid

The situation with this type of localized magnetic field, a so-called "magnetic obstacle", was investigated both numerically and experimentally (Fig. 3). The velocity profiles which have been obtained by measurements using Ultrasonic Velocimeter DOP 2000 and by simulations are shown in Fig. 4.

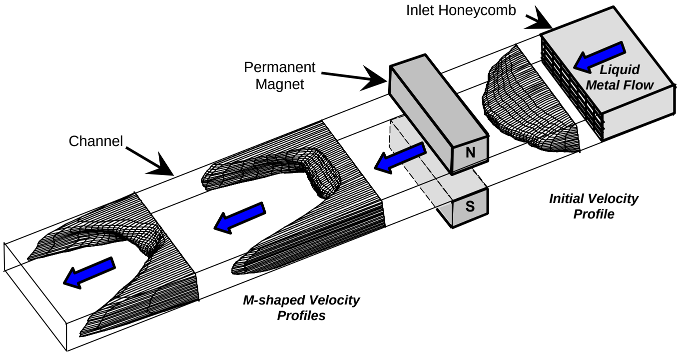


Fig. 4. Velocity distribution at the flow around the magnetic obstacle obtained by simulation [6]

The measured data reliably reproduced the flow patterns predicted by the numerical simulation. Thus, the vortices inside the applied magnetic field, connecting and attached vortices behind the magnet could be identified [6].

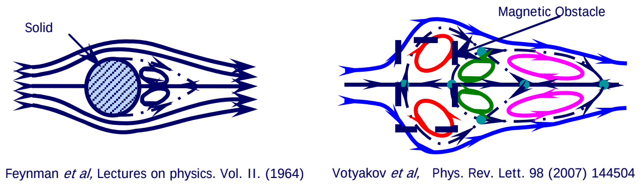


Fig. 5. Fluid flow around obstacles, solid vs. magnetic obstacle

We have experimentally investigated the influence of a steady non-uniform magnetic field on a liquid metal flow in a plane channel with insulating walls. This problem serves both as a frequently occurring MHD flow pattern interesting in its own right as well as a simplified physical model for magnetic braking in metallurgy.

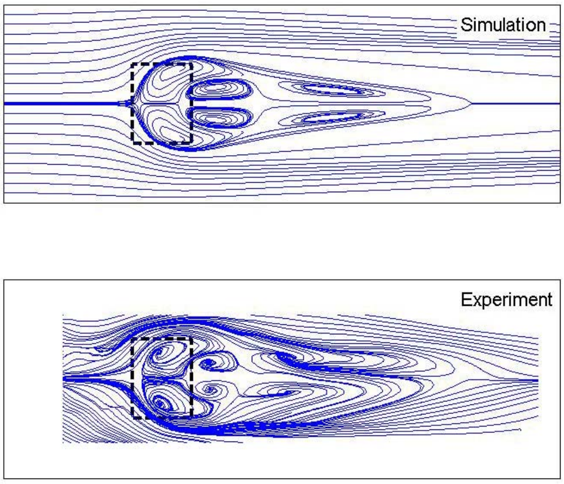


Fig. 6. Comparison of numerical simulation and experiment of the fluid flow around a magnetic obstacles

The experimental results for the magnetic field extending over the whole spanwise direction of the channel lead to a comprehensive database of velocity and electric potential measurements that will serve as benchmark data for future numerical simulations and development of MHD turbulence models. The experimental results for the strongly localized magnetic field, called magnetic obstacle, show that this type of flow is considerably more complex than expected. The experiments are found to be in excellent agreement with simulations of the flow around the magnetic obstacle (Fig. 6).

IV. Lorentz Force Velocimetry

Flow measurements using magnetic fields have a long history. In 1832 Faraday [7] attempted to determine the velocity of the Thames river near Waterloo bridge by measuring the electric potential difference induced by its flow across Earth´s magnetic field lines. Faraday´s method which consists in exposing a flow to a magnetic field and measuring the induced voltage using two electrodes has evolved into a successful commercial application known as the inductive flow meter [8]. Today his invention enjoys broad success in the chemical and food industries but has fallen short of solving the grand challenge of flow measurement in high-temperature melts like steel, aluminum or glass. While inductive flow meters are widely used for flow measurements in fluids at low temperature such as beverages, chemicals, and wastewater, they are not suited for flow measurement in metallurgy. The measurement of velocity in liquid metals is always a difficult problem because these materials are opaque and often hot and aggressive. Since they require electrodes to be inserted into the fluid, their use is limited to applications at temperatures far below the melting points at practically relevant metals. Thus, especially in situations where the liquid metals are at high temperature, as in metallurgy, the development of reliable contactless velocity measurement methods has far reaching consequences. Consequently there have been several attempts to develop flow measurement methods which do not require any mechanical contact with the fluid. Among them is the eddy current flow meter [9] which measures flow-induced changes in the electric impedance of coils interacting with the flow. More recently, a non-contact method was proposed [10, 11] in which a magnetic field is applied to the flow and the velocity is determined from measurements of flow-induced deformations of the applied field.

A research team at the Ilmenau University of Technology proposed in 2006 a new technique, which was termed “Lorentz force velocimetry (LFV)”, based on measuring the drag force on magnetic field lines which cross the melt flow [12]. This noncontact technique is suited for high-temperature applications because it is free from the unavoidable electrode corrosion problem that has plagued Faraday´s classical method.

When a liquid metal moves across magnetic field lines, as shown in Fig. 7, the interaction of the magnetic field with the induced eddy currents leads to a Lorentz force (with density $\boldsymbol{f} = \boldsymbol{j} \times \boldsymbol{B}$) which brakes the flow. The Lorentz force density is roughly

$$f \sim \sigma \upsilon B^2, \qquad (1)$$

where σ is the electrical conductivity of the fluid, υ its velocity, and B the magnitude of the magnetic field [13].

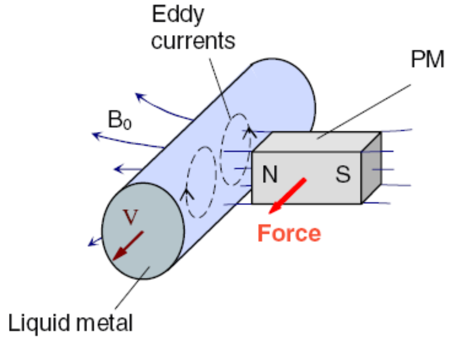


Fig. 7. Principle sketch of the Lorentz force velocimetry showing the action of a permanent magnet (PM) upon the flow of an electrically conducting fluid.

This fact is well-known and has found a variety of applications for flow control in metallurgy and crystal growth [14]. Equally obvious but less widely recognized is the fact that by virtue of Newton´s law, an opposite force acts upon the magnetic-field-generating system and drags it along the flow direction as if the magnetic field lines were invisible obstacles. This force is proportional to the velocity and conductivity of the fluid, and its measurement is the key idea of the new LFV method. Although the described phenomenon occurs no matter whether the magnetic field is generated by a (heavy) electromagnet or by a (lightweight) permanent magnet, it is thanks only to the recent advent of powerful rare earth permanent magnets and design tools for permanent magnet systems that a practical realization of this principle could now become possible [15].

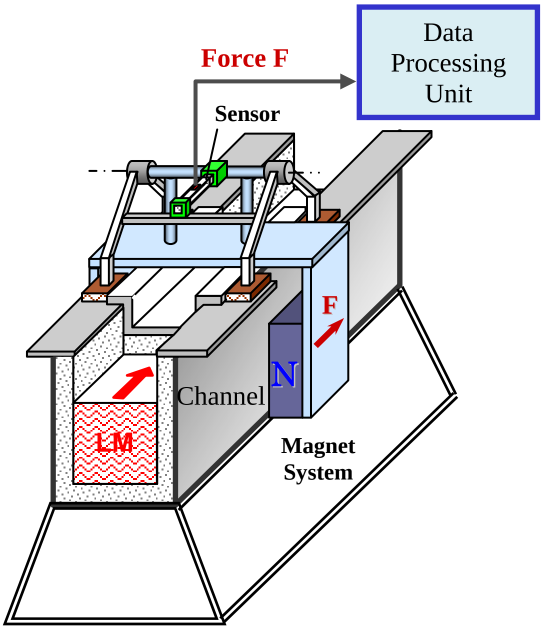


Fig. 8. Scheme of an industrial prototype of a Lorentz force anemometer applied to liquid metal (LM) flowing in a channel

The work on Lorentz force velocimetry is potentially of high interest to the materials processing community and will be further developed with industrial partners (Fig. 8).

The results of the experimental investigations form a comprehensive database have been made available to the MHD community and can be used by researchers in academia and industry for validation of home-made as well as commercial computational fluid dynamics software.

V. Controlling of Liquid Metal Free Surfaces

The development of an electromagnetic system for contactless closure of furnace crucibles, so-called “electromagnetic plug”, is a fascinating and scientifically still open problem of applied magnetofluiddynamics. To enter this problem, experimental and analytical studies of the modelling systems “Annular Gap” and “Drop” have been initiated. There are several industrial applications where these problems have to be considered, e.g. continuous steel casting (Fig. 9) or crucible free evaporation of liquid metal (Fig. 10).

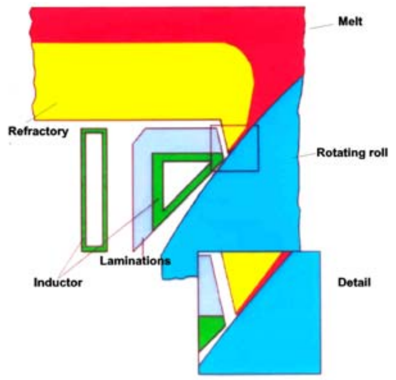


Fig. 9. Continuous steel casting and stopping the melt flow in the gap by means of electromagnetic fields

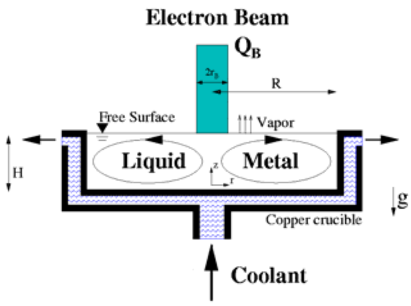


Fig. 10. Crucible free evaporation of liquid metal

During the experiments turns out that there is a new so far not known instability process caused by the interaction of liquid metal surfaces with high frequency magnetic fields [16, 17]. Even if this is from basic research point of view a nice feature, it was unfortunately not good news seen from the point of view of industrial applications. The liquid metal surface in a vertical gap remains stable if there is applied an electromagnetic compressive force acting orthogonally downwards to the surface as long as the magnetic pressure will not exceed a certain critical value. For pressures exceeding the critical value so-called “pinch instabilities” can be observed (Fig. 11), i.e. small initial distortions increase exponentially and built in very short time “pinch channels” which can punch through down to the crucible bottom.

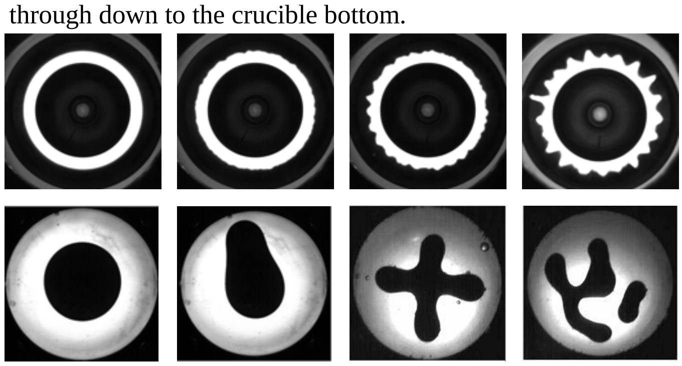


Fig. 11. Pinch instability in a liquid metal sheet: temporal development of the free surface, for „Annular Gap“ (*upper row*) and „Drop“ (*lower row*).

On the way to the development of electromagnetic plugs this effect forms an obstacle which has never be seen before in this clearness. From scientific point of view the new instability is an expression of universality of the nonlinear structuring process, because it is similar to the Saffman-Taylor-instability in porous media and in Hele-Shaw-cells as well as to the Mullins-Sekerka-instability during solidification of binary alloys. On the other hand, the investigation of this instability opens the perspective to describe the difficulties of the development of electromagnetic plugs very precisely. It will further provide the chance to search for possibilities to their suppression, e.g. by active controlling.

In the experiment "Annular Gap" (Fig. 12) was found that increasing the magnetic field leads to several free surface deformations like capillary waves, static undulations or electromagnetic pinches.

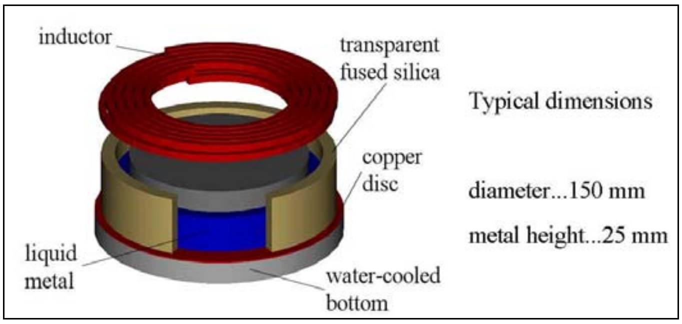


Fig. 12. Experimental setup for studies of the "annular gap"

Whereas the wave number is reciprocal proportional to the current penetration depth, the intensity of the waves depends on the magnitude of the magnetic field and the gap length. The wave spectrum of static deformations in the frequency range of 20 kHz – 50 kHz does not depend upon the frequency. If the magnetic field intensity exceeds a critical value an electromagnetic pinch will appear. The critical value is proportional to the gap length and decreases with increasing frequency. It can be well predicted using well-known analytical models like Hele-Show-Cell. The achievable electromagnetic pressure before pinching is proportional to the square of the magnetic field provided that the gap height is larger than the penetration depth. The achievable pressure itself is frequency independent in the frequency range of 2 – 5 kHz.

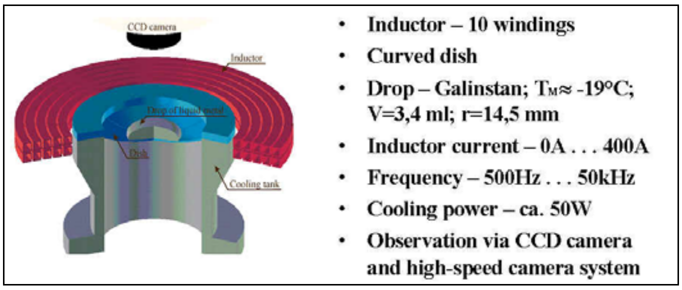


Fig. 13. Experimental setup for studies of the "drop"

The liquid metal drop (Fig. 13), below a critical inductor current, will be pressed together axis-symmetrically, with linear increasing of its height (Fig. 14). After further increase of the current the drop becomes unstable and oscillating waves along the drop circumference are formed (Fig. 15). The wave number depends on the drop volume and penetration depth (Fig. 16). The critical magnetic pressure has been estimated with respect to the drop volume and frequency, but the oscillation frequency is significantly less than that of the magnetic field [18, 19].

There have been designed experiments for studying the deformation of free surfaces of liquid metals influenced by an alternating magnetic field in the frequency range of 0.5 – 300 kHz. Main interest was addressed to the appearance of instabilities because they could become important for industrial applications.

Finally, results have been used by Schott AG, Mainz / Jena, and Doncasters Precision Casting, Bochum.

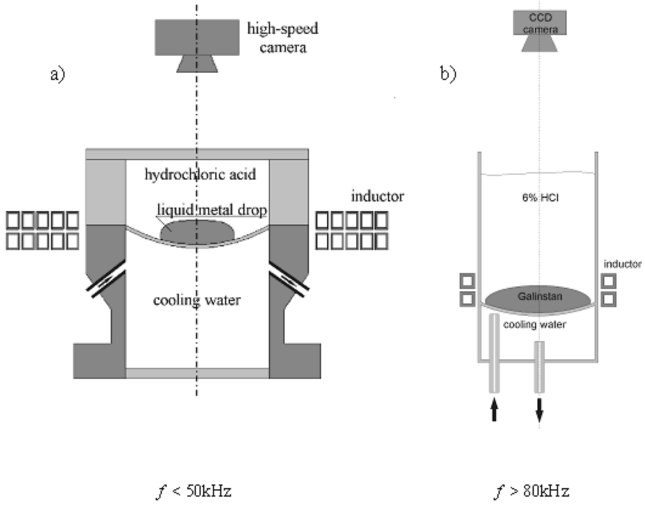


Fig. 14. Setup for experiment with metallic drops, with modification of parameters: critical current I_C, frequency f, drop volume V.

Fig. 15. Shape deformations of liquid metal drops in alternating magnetic field

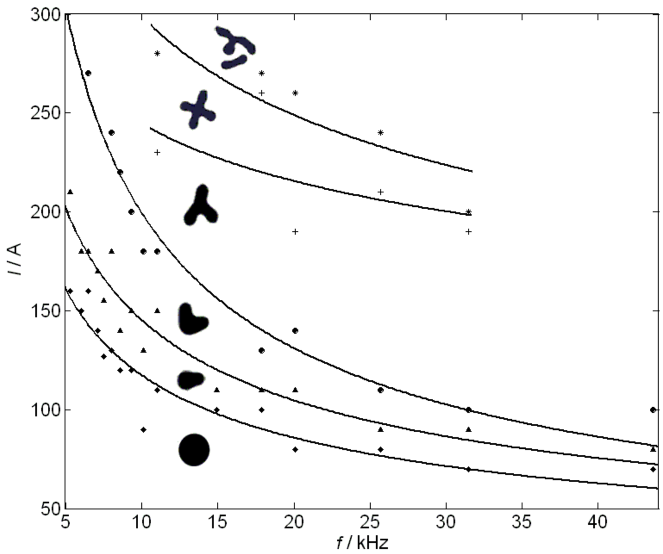


Fig. 16. Phase diagram of the inductor current vs. frequency for a liquid metal sheet (Galinstan), with thickness of 3mm.

VI. Electromagnetic Stirring of Glass Melts

Whereas electromagnetic stirring of liquid metals is used in metallurgy since more than 20 years is stirring of glass melts still an open problem of magnetofluiddynamics. This is because of the much smaller electrical conductivity and the much larger viscosity of glass versus metallic fluids. Additionally, there has to be taken into account the very conservative attitude of the involved industry.

Thus, it was a big step forward in the research of magneto-fluiddynamics that for the first time was directly demonstrated how dedicated caused Lorentz forces influence the stirring of glass melts (Fig. 17) [20].

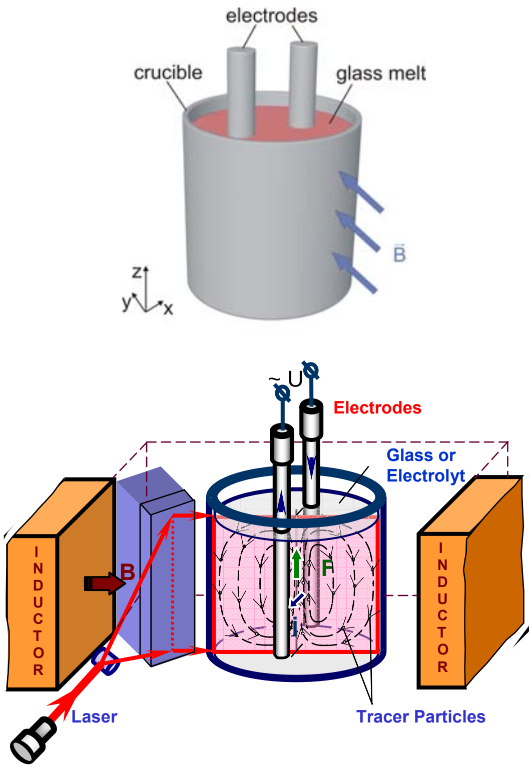


Fig. 17. Experimental setup for electromagnetic stirring of glass melts

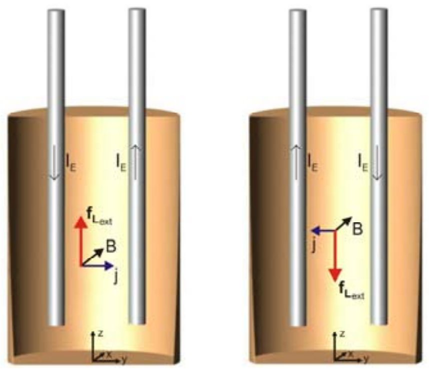


Fig. 18. Lorentz forces f_L impressed to the glass melts in opposite directions

The glass was heated in the crucible via the electrodes leading to a temperature profile with overheating in the region between the electrodes and strong temperature gradients. This situation will be changed considerably if an additional magnetic field is impressed leading to external Lorentz forces (Fig. 18). A Lorentz force acting upwards will increase the flow rate and reduce maximum temperature as well as the temperature gradient [20, 21].

The vertical temperature profile shows Fig. 19, where the right curve describes the behaviour without magnetic field and the left one the profile after switching on the magnetic field causing the Lorentz force. Both effects have been observed because of local in-situ temperature measurements [20].

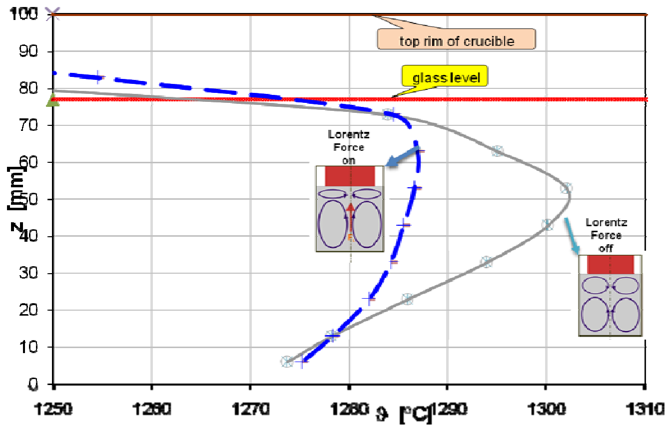
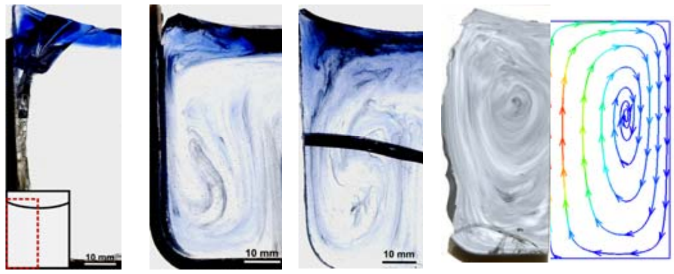


Fig. 19. Vertical temperature profiles, without magnetic field (*small circles*) and after turning on the external Lorentz forces (small triangles)

Measurements from solidified glass probes have also shown that the electromagnetic stirring improves the harmonization of the material (Fig. 20) [21].



(a) (b) (c) (d)

Fig. 20. Cuts trough the solidified glass probes,
(a) – after 5 min indirect heating, (b) – after 5 min direct heating,
(c) – after 5 min with Lorentz force upwards,
(d) - after 25 min with Lorentz force upwards, and simulated velocity profile

The effect has been confirmed by numerical flow simulations (Fig. 21) and analytical modelling, respectively [22, 23, 24].

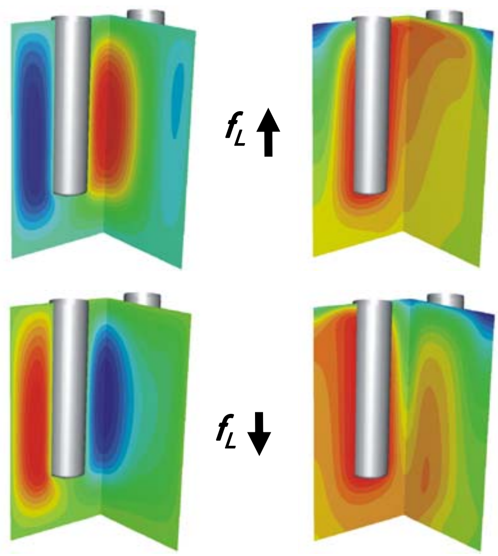


Fig. 21. 3D simulation of the flow rate distribution (velocity, *left*) and temperature profiles (*right*) for different directions of the Lorentz forces

These findings have already met the strong concerns of glass producing industries like *Schott Glas (Mainz)* in Germany leading to a close collaboration in this field.

VII. Identification of Fluid-Fluid Interface Deformations

Magnetic field tomography (MFT), a technique of source localization and source reconstruction using magnetic field measurements, has been intensively developed in recent years. It can be applied to reconstruct not only the current source in biomagnetism [25, 26, 27], but also the interface between two electrically conducting fluids with different electrical conductivities [28, 29]. This is of interest in studying the interfacial instabilities in aluminium reduction cells [30], velocity distributions in electrically conducting melts [31, 32], induced electrical currents in crystal growth [33] and in other electromagnetic processing of materials.

The measurement of magnetic fields is one of the key experimental techniques to reconstruct the unknown interface between two electrically conducting liquids [31-34] and there are many technical applications, like biomagnetism [27] and electromagnetic processing of materials [35, 36].

A. Physical Modelling

A typical aluminium reduction cell is composed of a series of rectangular cells with a length of several meters. When high electric currents (about 100 kA) are applied, the interface between the electrolyte of cryolite and liquid aluminium can be disturbed. The interface displacement is in the order of several centimeters and it can be considered as a perturbation at the interface. However, it is sometimes comparable to the depth of the electrolyte and liquid aluminium, and even spans the gap between two electrodes of the reduction cell so that it can lead to a short circuit, which can result in an inhomogeneous distribution of temperature and a larger consumption of energy. Since this is a hazardous phenomenon, it is of importance to reduce the undesired interfacial instabilities.

We have used a simplified model of the aluminium reduction cell (a cylindrical cell) to study the influence of the interface displacement on the perturbation of the magnetic field caused by an electric current through the interface (Fig. 22).

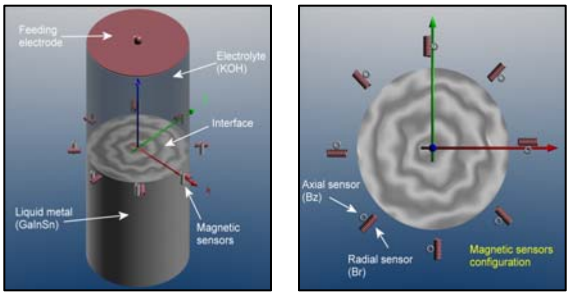


Fig. 22. Cylindrical two-fluid-cell as highly simplified model of an aluminium reduction cell with eight 2D fluxgate sensors (Fluxset® FXM-205) positioned on a circular ring near the cylinder wall

The current is driven by a DC voltage between the top electrode (low conducting fluid) and the bottom electrode (high conducting fluid). If the (plane) interface is distorted, the homogeneous magnetic field around the model cell will be affected by the spatial distribution of the interface displacement. If we can describe this as a harmonic oscillation, a periodic magnetic field modulation will be received at the magnetic field sensors near the interface. The amplitude of the signal depends on the spatial structure of the interface oscillation (mode) and its displacement magnitude.

B. Field Modelling

After computation of the magnetic field (forward calculation) in the vicinity of the interface around the cylinder for a given, well-defined interface deformation, special identification procedures can be applied to estimate interface deformation using tomographically measured magnetic field values (magnetic field tomography (MFT), Fig. 23) [28].

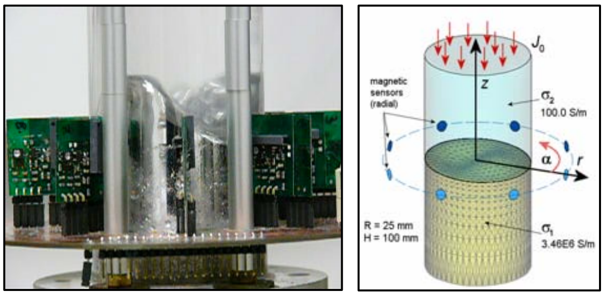


Fig. 23. Experimental setup of the cylindrical two-fluid-cell with the magnetic sensor ring (*left*) and the numerical model used for simulations (low-conducting electrolyte KOH, σ_2 = 100 S/m, high-conducting liquid metal Galinstan, σ_1 = 3.46E6 S/m, *right*)

The considered problem is shown in Fig. 23. Two fluids with different electrical conductivities σ_2 (up) and σ_1 (down) are placed in a long cylinder tank of the radius R. The tank walls are non-conducting. Along the axis of the cylinder a homogeneous electrical current density J_0 is applied. If the interface between fluids is flat, the current density J is homogeneous everywhere. As soon as the interface deviates from its flat shape, due to interfacial waves or an external forcing, the current density $\boldsymbol{J}$ becomes inhomogeneous near the interface. It leads to a perturbation of the magnetic field outside the cylinder which can be used for the identification of the interface shape. The perturbed interface shape function can be derived from Euler equation and the mass conservation law [37]. In the steady state it can be described as:

$$\eta(r,\alpha,t) \;=\; A(t)\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\eta^{*}_{mn}\cdot J_m\left(q_{mn}\frac{r}{R}\right)\cdot\cos m\alpha \qquad (2)$$

where A denotes the amplitude of the interface, η^{*}_{mn} are normalized mode coefficients, J_m are Bessel functions of the first kind, and q_{mn} is the $n-th$ solution of $J'_m\,(q_{mn}\,r/R) = 0$.

The value n is called the radial mode number and the value m the azimuthal mode number. It should be noted that in (1) axisymmetric modes ($m = 0$) are omitted due to the fact that they are producing only changes in the axial component of the magnetic field while the other components are equal zero and in that sense they are invisible by MFT system using only two components sensors (B_r, B_z).

C. The Inverse Problem

The identification of the interface shape between two fluids with different electrical conductivities carrying an electrical current is an inverse problem which can be solved by applying optimization techniques using measured magnetic field distributions. Moreover, such magnetic field measurement is also an important tool for non-destructive evaluation techniques used in experimental studies of magnetohydro-dynamics [28, 29]. Similar methods can be applied when electric probes are used to measure the electrical potential differences [38], for applications of ultrasonic transducers or if optical techniques for the measurement of displacement and velocity at the interface between two fluids have to be used.

The purpose of this study is the development of a magnetic field tomography system using a set of fluxgate sensors to measure the time-relevant distribution of magnetic field around a cylindrical cell containing two fluids with very different electrical conductivities. If a homogeneous electrical current density distribution is impressed and a well-defined non-axisymmetric interface shape is generated, radial and axial components of the magnetic field intensity will be induced. On the basis of the distorted electrical current field distribution and the resulting magnetic field, the interface shape has to be estimated by determining the parameters *A* and η^*_{mn} in equation (2) using multi-channel measurements of the magnetic field perturbation. This is the reason why the technique is called magnetic field tomography [28].

D. The Solution of the Inverse Problem

The solution of the inverse problem for the device under test (DUT) includes the determination of characteristic modes of the interface deformation as well as the estimation of their amplitudes. Because we can only use measured magnetic fields stochastic optimization techniques had to be applied.

Starting first with free available software codes for *Genetic Algorithms (GA)* and *Adaptive Simulated Annealing (ASA)*, we finally end up with evolution strategies (ES) and heuristic approaches.

Because the GA applications require much too much functions evaluations (i.e. in our case 3D field computations using FEM, see (3)),

$$CF = \frac{\sqrt{\sum_{i=1}^{N_S}\left[\left(B_{ri}-B_{ri}^0\right)^2+\left(B_{zi}-B_{zi}^0\right)^2\right]}}{\sqrt{\sum_{i=1}^{N_S}\left[\left(B_{ri}^0\right)^2+\left(B_{zi}^0\right)^2\right]}}\cdot 100\% \qquad (3)$$

we finally applied an ES(3,N) with a special mutation operator and combined this method with different regularization techniques [39]. The regularization, leading to an improvement of the ill-posedness of the inverse problem, can be achieved by adding the second term in (4) where small deviations from the dominant mode η_{mn} (or other modes, but with small amplitudes) are taken into account controlled by the regularization parameter α [40].

$$CF^{reg} = \left(\sqrt{\frac{\sum_{i=1}^{N_S}\left(B_i-B_{mi}\right)^2}{\sum_{i=1}^{N_S}B_{mi}^2}}+\alpha\cdot\sum_{m=1}^{M}\sum_{n=1}^{N}\left(\kappa-\eta_{mn}\right)^2\right)\cdot 100\% \qquad (4)$$

The regularization led to an improved convergence rate and to qualitatively better results for noisy data. The ES-based solutions turned out to be about three times faster than the former used GA versions.

But even in these strategies we have to evaluate many 3D FEM computations which are very time consuming. Thus, we decided to develop more efficient solution strategies using heuristic approaches. It is well-known that search space for stochastic optimization techniques can be reduced considerably by means of the so-called *principle component analysis (PCA)*. For our DUT we have to search first for the dominant mode of all possible interface shapes and its amplitude. This is an acceptable assumption in our case because only such stable oscillations of the interface have been studied in the experiments. It is known that with harmonic mechanical excitations only single modes can be generated, depending on the excitation frequency.

Three different heuristic approaches have been studied:

- PCA-GA [PCA + Genetic Algorithm (GA)]
- PCA-DS [PCA + Direct Search (DS)]
- PCA-CC [PCA + Cross-Correlation (CC)]

In the PCA-GA version a new genotype presentation has been defined which results in asignificant reduction of computing time compared to completely GA-based reconstruction techniques [41, 42]. In the PCA-DS version the whole search space is scanned which have been sorted before with respect to CF-values for given amplitudes [43].

The PCA-CC method uses a database which contains magnetic flux density distributions calculated for all possible modes (mode11 – mode33 for 8 sensors), an amplitude range from A = 2mm – 16mm (resolution of 1mm), and 72 x 21 sensor positions. The sensor positions have been spread regularly around the cylinder near the interface [44].

E. Interface Reconstruction

The identification of dominant modes in the interface using the cross correlation method turns out to be the most efficient heuristic approach for our DUT (Fig. 23). The FEM computations (with very high resolution, element size was about 1.5mm) has to be done only once. The interface identification requires only interpolations in this database.

If noisy data have to be used, the standard GA and ES versions failed for many interface modes. Thus, we finally designed a heuristic approach combining a spatial Fourier analysis, regularization (4) and a modified ES algorithm which was even faster than the GA methods. Table 1 shows the results for reconstruction of mode η_{21} with an amplitude of $A = 10mm$. For each ES version five independent runs have been performed (Table 1).

Table 1. Results of reconstruction of mode η_{21} with amplitude $A = 10mm$, using measured magnetic field data

Reconstruction Method	CF [%]	A [mm]	$\Sigma(\kappa-\eta)^2$	A_{av} [mm] *(5 iter.)*
PCA	15.0	8.3	0	-
ES (standard)	9.4	8.7	0.004	8.9
ES + regularization (α = 0.41)	10.2	8.8	0.0005	9.2
ES with rescaling	8.8	9.2	0.006	8.8

A visualization of the results is given in Fig. 24 where an optical observation from the experiment is compared to simulation results. The interface which is optically most closely to the original one was found with standard ES, whereas the best amplitude reconstruction has been achieved with ES with rescaling [39]. The amplitude error is in the same order as the noise level of magnetic field measurements [45]. Similar results have been found for other modes, e.g. mode η_{11}.

Fig. 24. Experimental observation (*middle*) and reconstruction results of different ES versions applied to measured magnetic field data (mode η_{21}), standard ES (*left*) and ES with rescaling (*right*)

From this study we can conclude:

- The proposed MFT-system (using 8 sensors) allows unique identification of all possible modes (modes $\eta_{11} \dots \eta_{33}$)
- Sensors should be positioned in the vicinity of B-field extrema and as closed as possible to the wall.
- The performance of the MFT-system strongly depends on the minimal sensor´s field resolution and on the possibility to position a sufficient number of sensors appropriately in the region of interest.

VIII. CONCLUSIONS

In the four parts of the project with their different fields of interest *braking effect, shaping, stirring,* and *measurements*, the teams of the research group have got the following main results:

- Design of an experimentally and numerically well-documented benchmark problem for the channel flow in inhomogeneous magnetic fields, to be used for further developments for electromagnetic braking tasks in metallurgy.
- Creation of an experimentally validated numerical program for the electromagnetic shaping of free liquid-metal surfaces as basis for the development of new systems for the electromagnetic sealing and support of highly reactive metallic liquids.
- Demonstration of the effect of electromagnetic stirring of a non-transparent glass melt as basis for an effective fining, for melt homogenization process, and controlling the characteristics of the glass products.
- Development of a new technique for the determination of liquid flow phenomena by contact-free observation of the movement of interfaces based on computerized magnetic field tomography.

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