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Electrically Induced Instabilities of Liquid Metal Free Surfaces

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Abstract

The dynamic behaviour of liquid metal submitted to a high-frequency magnetic field is investigated experimentally. We study both a liquid metal drop placed on a curved glass plate and a liquid metal surface confined in a thin annulus gap. We observe several drop instabilities depending on drop volume and magnitude and frequency of the applied field as well as various deformations of the free surface depending on frequency and field magnitude.

Introduction

High-frequency magnetic fields can be effectively used to shape and to control free surfaces of electrically conducting liquids like liquid metals, see Moreau [1] and Davidson [2] for an overview. Fautrelle et al. [3] study the dynamic behaviour of liquid metal drops in low-frequency magnetic fields. They show that for low values of the magnetic field, the wave pattern is axisymmetric and the oscillation frequency is identical to that of the electromagnetic forces. For larger magnetic field amplitudes, the observed waves are structured, but no longer axisymmetric. For even larger magnetic field strengths, a peculiar chaotic pattern appears, characterized by "fingers" and cavity formation. They observe, that under different conditions (electromagnetic fields), the amplitude of 2D azimuthal modes increases upon increasing the frequency of the field. In a theoretical study, Fautrelle and Sneyd [4] find that the instability of a liquid metal free surface submitted to a parallel alternating magnetic field sets in when the magnitude of the magnetic field exceeds a certain critical value B_c.

Within this context we study experimentally the effects of a high-frequency magnetic field on the dynamical behaviour of liquid metal surfaces. The results of the experimental observations are in good agreement with predictions of an analytical model.

1. Experimental Methods

In both experimental configurations the electromagnetic field is generated by an inductor supplied with alternating electrical current $I \cos(2\pi t)$. We increase the feeding current within the range $0 < I < 350$ A and vary its frequency within the range 20 kHz < f < 50 kHz.

As a test liquid we use the alloy Indium-Gallium-Tin called Galinstan. This metal shows a melting temperature of –19°C allowing precise measurements at room temperature. To avoid the oxidation of the free surface, the surface is fully covered by diluted hydrochloric acid or diluted sodium hydroxide. The liquid metal shows the following properties at room temperature: electrical conductivity $\sigma = 3.46\ 10^6$ S/m, density $\rho = 6440$ kg/m^3, surface tension $\sigma_S = 0.718$ N/m, and a static contact angle of $\Theta = 168°$.

The eddy currents induced in the liquid metal lead to an overall rise in temperature, thereby changing material properties like electrical conductivity and surface tension. These unwelcome Joule heat losses can only partly be removed through intensive water-cooling, limiting each experimental run to only a few seconds. All the measurements take place in the range between 30°C and 60°C.

The used generator allows the frequency to be adjusted only in discrete steps of some kHz. The inductor current is measured by using a shunt and a spectrum analyzer device.

During the experiments we observe the free surfaces shapes from above via a high-speed camera taking up to 307 frames per second. The maximum resolution is 1024 x 1024 pixels, with a colour depth of 8 bit. Due to the finite camera memory of 512 MB the recording length is limited to t = 6.65 s.

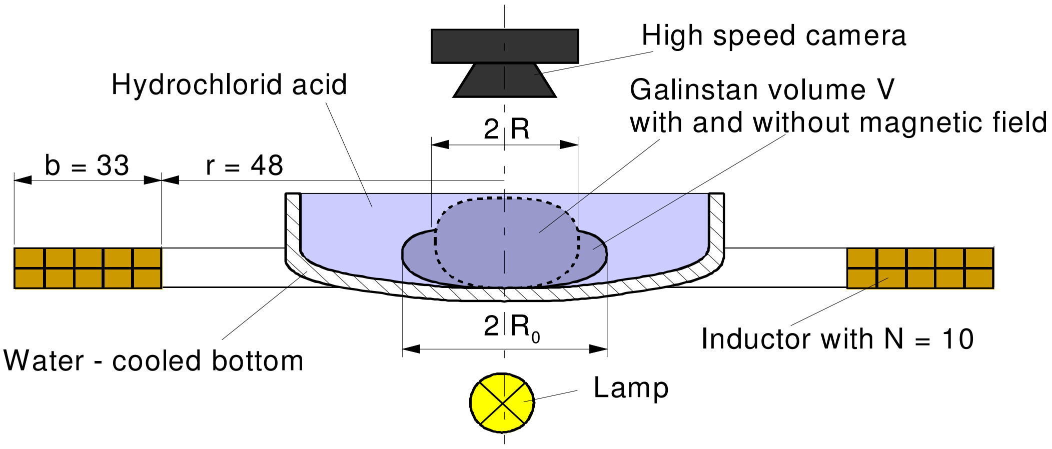

Fig. 1. Experimental set-up for the drop

2. Drop Experiment

In this model experiments, Kocourek et al. [5] study the static deformation of a circular liquid metal drop due to an electromagnetic pressure that is generated by a high-frequency magnetic field. Applications of this investigations include electron–beam evaporation, laser welding and cold crucible technologies.

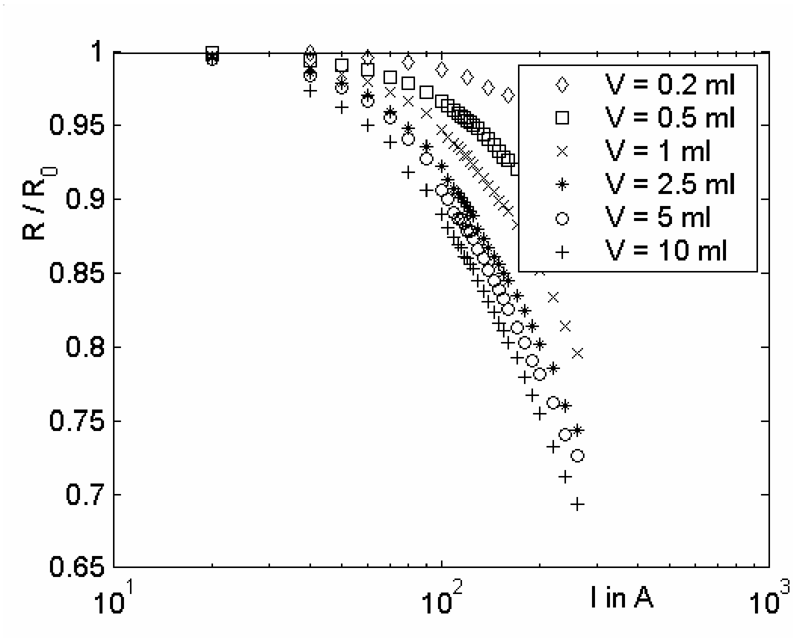

Fig. 2. Static drop deformations (squeezing) at 20 kHz

The test facility for the liquid metal drop experiment is show in Fig. 1. The used experimental techniques allow us to measure static drop deformations R/R_0 as well as the critical current I_c for different frequencies and drop volumes V. For relatively small value of the inductor current I, the high-frequency field results in a stable symmetrical drop squeezing. Initially flat drops (due to gravity) show a nearly hemispherical shape when an inductor current of a frequency of 20 kHz is switched on. Fig. 2

summarizes our experimental results on drop squeezing. It shows the normalized drop radius R/R_0 as function of the drop volume V, where R_0 denotes the drop radius without magnetic field. At first, small drops are inherently stabilized by surface tension. Upon increasing the inductor current beyond a certain value, the static shape of the drop becomes unstable. We observe the onset of drop oscillations (waves in the $r–\varphi$ plane).

The experimental findings are illustrated in Fig. 3. Upon increasing the Volume V, we observe that the mode number m of the exited axisymmetric waves increase likewise. For V = 1 ml we observe a cigar-type instability with mode number m = 2 (see Fig. 3 left) while for V = 5 ml the first unstable mode shows a triangular symmetry with m= 3 (see Fig. 3 right). As mentioned before, for V < 0.5 ml we are unable to detect any instability. In fact, we cannot rule out that this state becomes unstable at some higher value of the current I that lies beyond our experimental feasibility.

Fig.3. Drop deformations at current I = 100 A, frequency f = 20 kHz at mode 2 and 3

Fig. 4 shows the corresponding stability diagram. Here the critical current I_c is plotted against the volume V. Beneath the curves, i.e. $I < I_c$, we observe stable circular drops squeezed by the induced electromagnetic pressure. Above the curves, i.e. $I > I_c$, these static states are unstable and waves of a particular mode number m and oscillation frequencies f_c are observed. Upon increasing the current the first unstable mode is characterized by m = 2. This mode corresponds to drop oscillations of cigar-type shape as shown in Fig. 3 (left). This mode is present in the range 0.5 ml < V < 5 ml. At small drop volume, the critical current I_c decreases rapidly with increasing V but at higher values of V it starts to increase. In this range a transition to mode number m = 3 with triangular symmetry takes place, cf. Fig. 4 (right). This scenario is repeated at a volume of about V = 10 ml where the transition from m = 3 to m = 4 occurs, i.e. the transition from modes with triangular symmetry to modes with square symmetry.

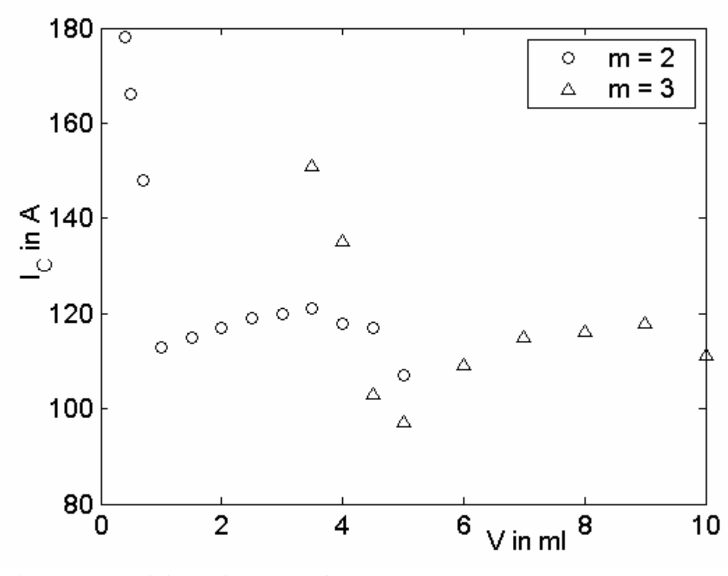

Fig. 4. Stability diagram for 20 kHz at mode m = 2 and 3

3. Annulus Gap

In the second model experiment, Mohring et al. [6] study the electromagnetically induced deformation of a free surface confined in an annual gap. The motivation for these investigations comes from electromagnetic slit-sealing.

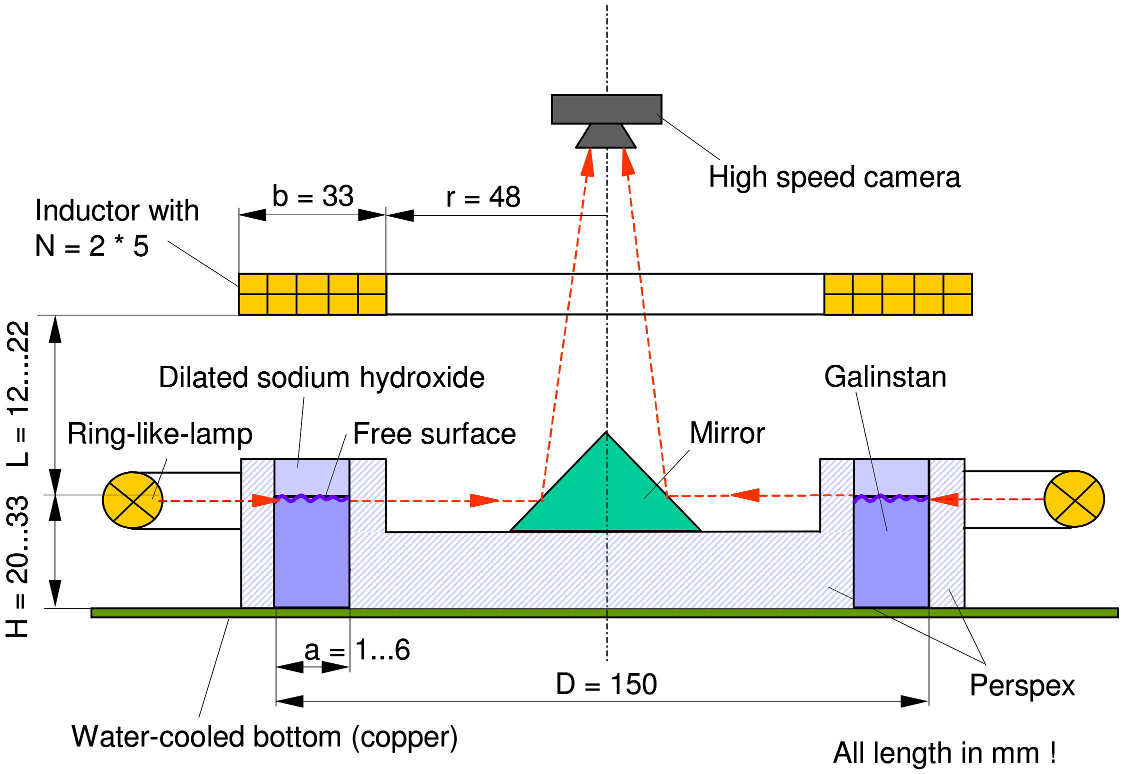

Fig. 5. Investigated arrangement for the annual gap

The apparatus used is shown schematically in Fig. 5. The characteristic dimensions are the annulus width a, the outer annulus diameter D, the fluid height H and the coupling gap L. The set-up consists of a water-cooled bottom made of copper. The inner and outer walls of the annulus are formed by circular rings of transparent perspex of thickness 10 mm. The width of the annulus is varied by using inner cylinders of various diameters. The gap of the annulus is filled with Galinstan. The coupling gap L can be adjusted by a special device sustaining the bottom. The deformations of liquid metal surface are observed from above by a high-speed camera using a special mirror in the centre. During the measurements we vary the electrical parameters like the frequency f and the inductor current I.

At a first value I of the inductor current the initially undisturbed flat surface becomes unstable to small-amplitude waves characterized by a certain wave number that depends strongly on inductor frequency. The amplitude of the waves increases upon increasing I.

Upon another slight increase of the inductor current, these surface oscillations are superseded by high-amplitude static deformation of sine wave shape. This shape, shown in Fig. 6 (left), represents a frozen state, i.e. the position of the maximum is nearly time-independent. The observed wavelength λ is dependent on both geometrical and electrical parameters. The static shape is the result of minimizing the total energy of the free surface consisting of: (i) the electromagnetic energy, (ii) the potential energy, and (iii) the energy of surface tension.

At slightly higher values of the critical inductor current I_c, the state of static surface deformation switches over into a further kind of instability, the electromagnetic pinch. At this critical value, the electromagnetic pressure rises rapidly in the troughs and exceeds the stabilizing effects of hydrostatic pressure and surface tension pressure. A thin channel growing downwards is formed in the trough of the wave. Fig. 6 (right) shows such a pinch channel in the liquid metal. A drop-like cavity filled with sodium hydroxide is formed at the end of the channel. Due to the proximity effect, the electromagnetic forces on the channel walls act repulsively to each other and thus stabilize the thin channel for a short moment. However, the cavity is very unstable.

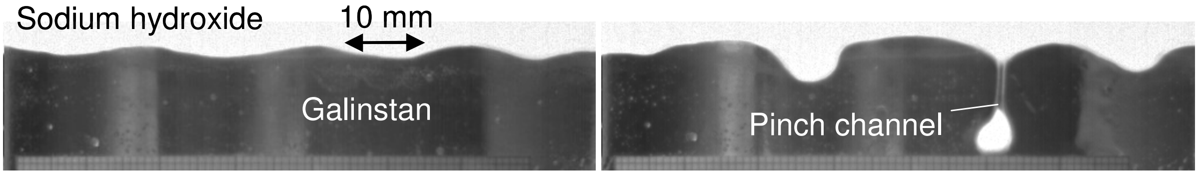

Fig. 6. Free surface for a = 3 mm, H = 24 mm, L = 17 mm and f = 21,9 kHz with static deformation at I = 127 A (left) and with pinch effect at I = 130 A

We repeat the experiments to determine the dependence of the critical inductor current I_c on the geometrical parameters a and L, and on the current frequency f.

Fig. 7 shows the critical current as a function of the frequency at various gap widths for a constant fluid height ($H = 24\ \mathrm{mm}$) and coupling gap ($L = 17\ \mathrm{mm}$). The measured points are interpolated by the dashed lines using a function according to

$$I_c(f) \propto f^{-\alpha}.$$

We obtain higher values of α for lower gap widths. The dotted line is a theoretical curve which was calculated by Karcher and Mohring [7]. They perform a linear stability analysis using both the skin depth and the Hele-Shaw approximation. For the onset of a long-wavelength instability this model predicts an exponent of $\alpha = 1/4$. The measured exponent $\alpha(a = 1\ \mathrm{mm}) = 0.2323$ is only a little smaller then this theoretical value.

The critical current for the onset of the pinch is also investigated by varying the geometrical parameters L, a, and H. It is found that these parameters only show an electromagnetic effect as both the hydrodynamic and the surface tension pressure remain unchanged.

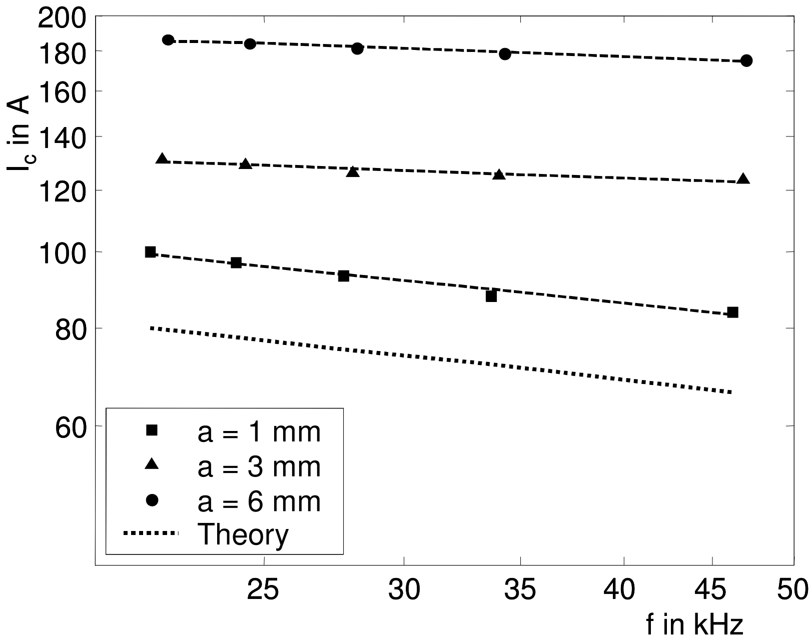

Fig. 7. Critical inductor current in dependence on frequency f width and frequency f for H = 24 mm and L = 17 mm

Conclusions

We have studied experimentally the dynamics of both liquid metal drops and a free liquid metal surfaces in an annulus affected by a high-frequency electromagnetic field. In the drop experiment, at a small magnetic field, we observe static symmetric drop squeezing. However, after increasing the field ($I > I_c$) these static states become unstable against waves of a particular mode number m. In the experiment with the annulus, upon increasing the inductor current we observe different kinds of instabilities. At low values of the inductor current we observe oscillating capillary surface waves with a wavelength corresponding to the electromagnetic skin depth. At higher values of the current, we find a static surface deformation with a wavelength depending on geometrical and electrical parameters. Eventually, the onset of an electromagnetic pinch is observed. We find a good qualitative and quantitative agreement of the data with predictions of an analytical stability analysis.

Acknowledgements

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