Dynamics of liquid metal droplets and jets influenced by a strong axial magnetic field

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Abstract. Non-contact electromagnetic control and shaping of liquid metal free surfaces is crucial in a number of high-temperature metallurgical processes like levitation melting and electromagnetic sealing, among others. Other examples are the electromagnetic bending or stabilization of liquid metal jets that frequently occur in casting or fusion applications. Within this context, we experimentally study the influence of strong axial magnetic fields on the dynamics of falling metal droplets and liquid metal jets. GaInSn in eutectic composition is used as test melt being liquid at room temperature. In the experiments, we use a cryogen-free superconducting magnet (CFM) providing steady homogeneous fields of up to 5 T and allowing a tilt angle between the falling melt and the magnet axis. We vary the magnetic flux density, the tilt angle, the liquid metal flow rate, and the diameter and material of the nozzle (electrically conducting/insulating). Hence, the experiments cover a parameter range of Hartmann numbers $Ha$, Reynolds numbers $Re$, and Weber numbers $We$ within $0 < Ha < 440$, $340 < Re < 4500$, and $0.09 < We < 12.1$. As major results we find that under the influence of the strong magnetic field, droplet rotation ceases and the droplets are stretched in the field direction. Moreover, we observe that the jet breakup into droplets (spheroidization) is suppressed, and in the case of electrically conducting nozzles and tilt, the jets are bent towards the field axis.

Keywords: jet instability, magnetohydrodynamics, Lorentz force

1. Introduction

During the last decades, Electromagnetic Processing of Materials (EPM) have developed to a powerful engineering tool to influence or to control high-temperature processes of electrically conducting fluids like liquid metals (for an overview see [1]). In those processes, one exploits the fact that due to the interactions between a moving conductor and an externally applied magnetic field, the so-called Lorentz forces are induced. These forces can be used for stirring and melting processes, i.e. enhancing heat and mass transfer, as well as for the development of non-contact flow measurement techniques [2, 3, 4, 5]. In this paper, we focus on the effects of electromagnetic shaping and stabilization of liquid metal free surfaces [6, 7, 8, 9, 10]. In more detail we investigate the effect of an axial magnetic field on a liquid metal droplet and jet flow. A liquid jet which flows out from a nozzle to an ambient gas is inherently unstable. Plateau [11] has shown that, due to surface tension, an infinite jet breaks up into sections comparable to the initial circumference which have less total surface area than the original cylindrical jet. Rayleigh [12] showed that by neglecting the viscosity of the liquid, the ambient fluid, and gravity, the system is characterized by unstable perturbations of different wavelengths, for which the interfacial perturbations are
amplified, i.e. the cylindrical shape becomes morphologically unstable. Rayleigh concluded that the maximum instability, in which perturbations grow faster, occurs at $\lambda_{\text{crit}} \approx 9r_0$, where $r_0$ is the radius of the original cylindrical jet. Favoring by surface tension, $\lambda_{\text{crit}}$ triggers the breakup of the liquid jet into droplets, and therefore defines the typical droplet size. Chandrasekhar [13] treated the general Navier-Stokes case and investigated the effect of the viscosity on the breakup. $\lambda_{\text{crit}}$ can be shifted to larger or shorter wavelengths depending on the viscosity of the liquid. Chandrasekhar also investigated the effect of an axial magnetic field on this so-called capillary instability and concluded that a magnetic field of sufficient strength will stabilize the jet for varicose deformations of all wavelengths.

In this paper we validate experimentally the stabilizing effect predicted by Chandrasekhar for droplet and liquid metal jet flows under a strong axial magnetic field. The working fluid is GaInSn in eutectic composition and the steady and homogeneous axial magnetic field is produced by a 5 T cryogen-free superconducting magnet (CFM). We vary the diameter ($d_1 = 0.9 \text{ mm}$, $d_2 = 1.55 \text{ mm}$, $d_3 = 2.2 \text{ mm}$) and material (electrically conducting/insulating) of the nozzle, the magnetic field strength ($B_0 = 0 \ldots 5 \text{ T}$) and the liquid metal flow rate. We have focused at the beginning of this paper on the results using the biggest diameter, for which the stabilizing effect is more pronounced, covering three specific flow regimes: 1- droplet flow, 2- transition from droplet to continuous jet, and 3- continuous jet flow. Finally, we investigate the effect of electrically conducting and electrically insulating nozzles on a liquid metal jet, when the applied magnetic field is tilted by an angle of $\varphi = 5^\circ$ with respect to gravity. In this case we vary the diameter of the nozzle while maintaining constant the Reynolds number and the magnitude of the applied magnetic field.

The structure of the paper is as follows: in section 2 we presents a brief introduction of droplet and jet flows with and without the influence of an axial magnetic field. Here, we review the definition of all dimensionless parameters that describe the physics involved. In section 3, the experimental set-up is described followed by section 4, which shows the main results. Finally, section 5 gives a summary of the principal conclusions.

2. Capillary instability of a liquid metal jet under a strong axial magnetic field

The flow regimes in droplet and liquid metal jet flows is a complex interaction between the effects of surface tension, inertia and friction. These effects are parameterized by the dynamic scaling ratios Reynolds $Re$, Weber $We$ and Ohnesorge $Oh$ numbers defined by the relations

$$Re = \frac{\mu_0 d}{\mu}, \quad We = \frac{\mu_0^2 d}{\gamma}, \quad Oh = \frac{\sqrt{We}}{Re} = \frac{\mu}{\sqrt{\rho \gamma d}} \quad (1,2,3)$$

Here, $u_0$ is the characteristic velocity (average velocity inside the nozzle) and $d$ is the characteristic length (nozzle diameter). $\rho$, $\mu$ and $\gamma$ denote the density, the dynamic viscosity and surface tension of the liquid, respectively. $Re$ and $We$ represent the ratio of inertia to viscous forces and the ratio of inertia to surfaces tension forces, respectively. The breakup regimes of a given liquid jet flow depends on the corresponding values of $Re$ and $Oh$. An example of a phase diagram $Oh$ vs $Re$ is depicted in [14]. Droplet flow occurs at low $We$ and $Oh$ numbers. For higher $Oh$ and $We$, the flow regime of a liquid jet can be classified according to Lin [15] as: Rayleigh regime, first wind-induced regime, second wind-induced regime and atomization regime. Rayleigh and first wind-induced regime are characterized by low jet velocities, whereby the diameter of the droplets are larger than the jet diameter. For high speed jets, second wind-induced and atomization regime, the breakup is due to the growth of short-wavelength surface waves generating droplets smaller that the diameter of the jet.

Chandrasekhar [13] investigated the influence of an axial magnetic field on the capillary instability of an electrically conducting jet. Among others, he analyzed the cases in which the liquid is inviscid and shows a finite electrical conductivity, i.e. a finite resistivity. Here,
the electrical resistivity \( \eta \) is defined as \( \eta = (4\pi \mu_m \sigma)^{-1} \), where \( \mu_m \) and \( \sigma \) are the magnetic permeability and electrical conductivity of the liquid, respectively. The effects of an axial magnetic field on the capillary instability of an electrically conducting jet are parameterized by the dimensionless group \( \chi \), Hartmann number \( Ha \), and the electromagnetic interaction parameter \( N \) defined by the relations

\[
\chi = \frac{\mu_m H^2}{4\pi \eta} \sqrt{\frac{r_0^3}{\rho \gamma}}, \quad Ha = \sqrt{NRe} = B_0 d \sqrt{\frac{\sigma}{\rho \nu}}, \quad N = \frac{\sigma B_0^2 d}{\rho u_0}. \tag{4.5.6}
\]

Here, \( l_\nu = \nu^2 \rho (\gamma)^{-1} \) is a viscous lengthscale according to Eggers [16] and \( H \) is the auxiliary magnetic field, where \( B_0 = \mu_m H \). \( Ha \) and \( N \) represent the ratio of Lorentz forces to shear forces and the ratio of Lorentz forces to inertia forces, respectively. \( Ha \) is typical used for scaling the magnitude of \( B_0 \) in a given system. The main conclusion is that an axial magnetic field \( B_0 \) of sufficient strength will stabilize the jet for capillary instability (varicose deformations) of all wavelengths, whereby the wavelength \( \lambda_{crit} \) increases. For a liquid with zero viscosity and zero resistivity, the capillary instability can be totally suppressed. In the case of liquid metals, which in general have finite \( \eta \), the stabilizing effect is present when the parameter \( \chi \) exceeds the value of 6. Table 1 compares the values of \( \chi \) for mercury, lithium, sodium and GaInSn for the same values of \( r_0 \) and \( B_0 \) like our experiments presented in section 4. According to table 1, we could expect a stronger suppression of capillary instability for hot liquids like lithium and sodium than for GaInSn or mercury under the influence of an axial magnetic field.

| Liquid metal | \( \rho \) (kg/m\(^3\)) | \( \nu \) (m\(^2\)/s) | \( \sigma \) (MS/m) | \( \gamma \) (N/m) | \( \chi \) |
|-------------|----------------|----------------|----------------|----------------|---------|
| Mercury @450°C [17] | 13.5 \cdot 10^3 | 1.15 \cdot 10^{-4} | 1 | 0.48 | 4.3 |
| Lithium @450°C [17] | 491 | 7.1 \cdot 10^{-7} | 3.1 | 0.371 | 74.9 |
| Sodium @450°C [17] | 844 | 3.0 \cdot 10^{-7} | 4.3 | 0.164 | 120.8 |
| GaInSn @~ 26°C [18] | 6.33 \cdot 10^4 | 3.3 \cdot 10^{-7} | 3.3 | 0.585 | 17.8 |

Table 1. Summary of basic thermophysical and electrical properties for different liquid metals and the corresponding value of \( \chi \) according to (4) for \( r_0 = d/2 = 1.1 \text{mm} \) and \( B_0 = 3 \text{T} \) like in our experiments.

3. Experimental set-up
The experimental set-up is depicted in figure 1. A syringe pump drives the liquid metal from the collecting vessel to the centering device at which the respective nozzle is fixed. Centering device and nozzle are located in the middle of a cryogen-free superconducting DC magnet (CFM) which produces an homogeneous axial magnetic field \( B_0 \). As a simple reciprocating pump, the syringe pump works in two modes. In the first one, it pumps GaInSn from the collecting vessel into its barrel. In the second one, it pumps the collected liquid into the centering device. The intake and outtake of GaInSn from and into the pump are controlled by a valve and the pressure in the tube is measured by a manometer. At the end of the centering device, which ensures an accurate angle between the applied magnetic field and the jet, the liquid metal flows through the nozzle and falls finally into a plastic funnel. At the outlet of the funnel the liquid metal then flows due to gravity to the collecting vessel. A high-speed camera placed on top of the magnet records the projection of the jet or droplet flow on a mirror. The light needed is given by a LED also placed in the middle of the magnet as well as the mirror.

The flow rate in the experiments for \( d = 2.2 \text{mm} \) lies between 11.6 ml/min and 154.5 ml/min covering a range of \( 340 < Re < 4500 \) (0.09 < We < 12.1). The velocity \( u_0 \) used in the dimensionless numbers is obtain by dividing the flow rate by the cross-section of the nozzle.
Figure 1. Sketch of the experimental set-up for the observation of the stabilizing effect of an axial magnetic field on liquid metal droplet and jet flows. The set-up is composed of: 1- mid pressure syringe pump, 2 - manometer, 3- valve, 4- centering device (brass), 5- high-speed camera (fps=231), 6- mirror, 7- LED, 8- cryogen-free super conducting DC magnet, 9- plastic funnel and 10- collecting vessel.

\( \pi d^2 / 4 \). In our experiments, we have selected the following Reynolds numbers which correspond to 3 different flow regimes:

- \( Re = 340 \) (\( We = 0.09 \)): droplet flow
- \( Re = 1690 \) (\( We = 1.9 \)): transition from droplet to continuous jet flow characterized by discontinuous short-length irregular jets
- \( Re = 4500 \) (\( We = 12.1 \)): continuous jet flow (Rayleigh regime)

The magnitude of the applied magnetic field in the experiments starts at 0 T and it is gradually increased in 1 T steps until reaching 5 T. The magnetic field distribution in the center of the magnet, in which the liquid metal is observed, can be found in [19, 20]. In this area, the magnetic field is fairly homogeneous having about \( \partial B_0 / \partial r \approx 0.03 \) T/cm in radial direction and \( \partial B_0 / \partial z \approx 0.06 \) T/cm along the axis of the magnet. An homogeneous magnetic field produces no net electromagnetic force on droplets and/or jets. A high-speed camera is placed on top of the 5 T cryogen-free magnet and captures the dynamics of the flow at 231 frames per second. In our experimental set-up, the camera is capable to record droplet or jet flows up to a distance of about 7 cm away from the nozzle. The parameters taken into consideration are summarized in table 2.

| Parameter              | Value                      |
|------------------------|----------------------------|
| Nozzle diameter \( d \) (mm) | 0.9 , 1.55 , 2.2          |
| Material of the nozzle  | Brass (conducting) , PTFE (insulating) |
| Magnetic field \( B_0 \) (T) | 0 , 1 , 2 , 3 , 4 , 5      |
| Inclination of the magnet \( \varphi \) | 0° , 5°                    |
| \( Re \)               | 340 , 1690 , 4500          |
| \( We \)               | 0.09 , 1.9 , 12.1          |
| \( Oh \)               | \( 1.1 \cdot 10^{-3} , 8.8 \cdot 10^{-4} , 7.4 \cdot 10^{-4} \) |

Table 2. List of parameters.

4. Results
As explained in section 1, the results that will be presented at the beginning of this section correspond to the nozzle with diameter \( d = 2.2 \) mm in which \( 0 < N < 564.4 \), \( 0 < Ha < 436.4 \), and \( 0 < \chi < 49.5 \). For smaller diameters, i.e. \( d < 2.2 \) mm at \( Re = 340 \) and \( d < 1.55 \) mm at \( Re = 1690 \), there was no evident stabilizing effect of the magnetic field even by \( B_0 = 5 \) T. Figure
Figure 2. Droplet formation at the outlet of the electrically conducting nozzle made of brass for $Re = 340$, $d = 2.2$ mm, $\varphi = 0^\circ$, $B_0 = 0$ (upper sequence) and $B_0 = 5$ T (lower sequence).

2 presents a sequence of droplet flow ($Re = 340$) for 0 and 5 T flowing through the electrically conducting nozzle. It shows that the magnetic forces influence droplet formation just at the outlet of the nozzle. The strong axial magnetic field suppresses the growth of the droplet in radial direction, and therefore, it is forced to elongate streamwise. This same effect was also seen using the electrically insulating nozzle. However, the already deformed droplet maintains this form downstream until the bottom of the observable area. It appears that the influence of the magnetic field on the expected internal circulation patterns inside the droplet according to LeClair [21] is small and can not be identified based on the pictures taken by the high-speed camera. However, we have observed that $B_0 = 1$ T is sufficient for the droplets to align themselves with their axis into the direction of the magnetic field for every nozzle diameter. For a better understanding of this interaction between a liquid metal droplet under an axial magnetic field, we are currently preparing a numerical model of our experiments.

When the flow rate is increased up to $Re = 1690$, we observe that the capillary instability, spheroidization of the jet into droplets, is clearly suppressed. The discontinuous short-length jets have now characteristic top and bottom sharp tips which were already predicted by Eggers [22]. The shape of the jet segments with sharp tips appears to be caused by the complex interaction between the suppression of the radial velocity of the jet during the process of spheroidization under a strong axial magnetic field and the acceleration of the fall. Additionally, the breakup length is increased for $B_0 = 5$ T. We believe that with a magnetic field $B_0$ not much higher than the one considered in this paper, the capillary instability could be totally suppress, or at least sufficiently, resulting in long and continuous liquid metal jets at low $Re$ numbers. However, for $Re = 4500$, there was no visible effect of the magnetic field as in this regime the instability occurs further than the observable area of the camera. The flow in this case is strictly axial, and therefore, co-aligned with the magnetic field without able to generate a Lorentz force density in the liquid. This is the same reason that we did not observe any comparable differences with electrically conducting and insulating nozzles as the velocity field in the nozzle is parallel to the magnetic field (figures 3 and 4). In the next section, as now the velocity and the applied magnetic field are no longer co-aligned with each other, we clearly see a notorious effect on the dynamics of the jet using an electrically conducting nozzle.

One of the problems or disadvantages of working with GaInSn is that it gradually reacts with the ambient air generating oxide that, after a long period of runs, it may accumulate inside the nozzle. This will cause unwanted deflections of the jet that are not related to the physics involved. An example of this situation can be seen in figure 3 for ($Re = 1690, N = 4.6$) and in figure 4 for ($Re = 1690, N = 4.6$) and for ($Re = 4500, N = 1.7$).
Figure 3. Single images of GaInSn droplet and jet flows falling from an electrically insulating nozzle. $Re$ and $Ha$ numbers are maintained constant in the horizontal and in the vertical axis, respectively. The direction of the applied magnetic field $B_0$ and gravity $g$ are plotted as red and blue arrows, respectively. For $(Re = 1690, N = 4.6)$, a non-physical bending of the jet occurs due to accumulation of GaInSn oxide at the outlet of the nozzle.
Figure 4. Single images of GaInSn droplet and jet flows falling from an electrically conducting nozzle made of brass. $Re$ and $Ha$ numbers are maintained constant in the horizontal and in the vertical axis, respectively. The direction of the applied magnetic field $B_0$ and gravity $g$ are plotted as red and blue arrows, respectively. For ($Re = 1690$, $N = 4.6$) and ($Re = 4500$, $N = 1.7$), a non-physical bending of the jet occurs due to accumulation of GaInSn oxide at the outlet of the nozzle.
4.1. Tilted magnetic field
In this section, in contrast to the previous one, the magnetic field and gravity are not co-aligned but tilted $5^\circ$ with each other. In this case we focus on $Re = 4500$ characterized by a continuous liquid jet (Rayleigh regime). Figure 5 presents the results of conducting and insulating nozzles by different nozzle diameters and with and without axial magnetic field. We observe that when the diameter $d$ is increased while maintaining the same $Re$, i.e. $N$ is increased, the effect of wall conductivity is more pronounced. At $B_0 = 5$ T, the liquid metal is strongly deflected into the direction of the applied magnetic field at the outlet of the nozzle, whereas in the insulating nozzle case no effect was observed. As now the flow inside the nozzle is not parallel to the magnetic field, eddy currents and flow-breaking Lorentz forces are generated in this area. However, it appears that in the insulating wall case, the induced Lorentz forces are too weak to affect the dynamics of the jet as the induced eddy currents are forced to close in a smaller area. In the case of conducting walls, the induced eddy currents and Lorentz force density are stronger due to the fact that the overall electric resistance of the system is minimized.

| $d$ | $B_0$ | $H_a$ | $N$ |
|-----|-------|-------|-----|
| 0.9 mm | 0 T | 0 | 0 |
| 0.9 mm | 5 T | 178.4 | 7.1 |
| 1.55 mm | 5 T | 307.2 | 21.0 |
| 2.2 mm | 5 T | 436.1 | 42.3 |

**Figure 5.** Sequence of pictures of GaInSn jets ($Re = 4500$) falling from an electrically conducting (top) and an electrically insulating nozzle (bottom). The direction of the applied magnetic field $B_0$ and gravity $g$ are plotted as red and blue arrows, respectively. The magnetic field and gravity are tilted $\varphi = 5^\circ$ with each other.
5. Conclusions
We experimentally investigated the effect of an axial streamwise magnetic field on the suppression of capillary instability of a liquid metal jet and its influence on a droplet flow. In this paper, we have focused on three different Reynolds numbers which correspond to three breakup regimes ($Re = 340$, $Re = 1690$, $Re = 4500$). We have presented the results for the biggest diameter ($d = 2.2$ mm) where the interaction between the flowing liquid metal and the magnetic field is more predominant. The first breakup regime corresponds to droplet and the third one to a continuous jet flow (Rayleigh regime). We have observed that at $Re = 1690$, the transition from droplets to a continuous jet flow occurs characterized by discontinuous short-length irregular structures. In this regime, the applied magnetic field of 3 T was sufficient to stabilize these segments showing characteristic top and bottom sharp tips, whereby the length of breakup is increased. In the case of droplet flow, the tips of the droplets are aligned vertically with the magnetic field even by the smallest magnetic field considered in this paper (1 T) and for 5 T, the droplet is deformed and elongated in the direction of the magnetic field. The strong axial magnetic field seems to suppress the radial growth of the droplet at the outlet of the nozzle. For continuous liquid jets ($Re = 4500$), there was no observable effect of the axial magnetic field on the flow for neither electrically conducting nor electrically insulating nozzles. However, when the magnetic field is not co-aligned but tilted $5^\circ$ relative to gravity, the induced eddy currents and Lorentz forces are much stronger using the electrically conducting nozzle than the insulating one. The induced Lorentz forces are enough to deflect the liquid jet at the outlet of the electrically conducting nozzle into the direction of the magnetic field. Depending on the value of the interaction parameter $N$, the effect is less or more pronounced.

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