Dynamics of Falling Liquid Metal Droplets and Jets Influenced by a Strong Axial Magnetic Field

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Abstract

Non-contact electromagnetic shaping of liquid metal free surfaces is crucial in several metallurgic processes including bending or stabilization of jets in casting or fusion applications. In this context we experimentally study the influence of strong axial magnetic fields up to 5 T on the dynamics of falling droplets and jets. As a test melt we use GaInSn which is liquid at room temperature. In the experiments we vary the magnetic flux density, the tilt angle, the liquid metal flow rate, and the diameter and the material (conducting/non-conducting) of the nozzle. As major results we find that under the influence of the field, liquid metal droplets are stretched in the field direction, droplet rotation ceases, and the droplet axis aligns with the axis of the field. Moreover, we observe that jet break-up into droplets is suppressed and, for the case conducting nozzle and tilt, jets are bent towards the field axis.

Introduction

Electromagnetic Processing of Materials (EPM) developed to a powerful engineering tool to influence or to control high-temperature processes of electrically conducting fluids like liquid metal melts, see [1] for an overview. In those processes, one exploits the fact that due to the interactions of a moving conductor and an externally applied magnetic field, Lorentz forces are induced. These forces, either generated by static or time-dependent fields, can be used for non-contact stirring and mixing, breaking, and levitation, as well as for melting processes using induction heating. Another application is the development of non-contact flow measurement techniques. Details of all these applications are given in [2]-[8].

In this paper, we focus on the effects of electromagnetic shaping and stabilization of liquid metal free surfaces [9], [10], [11]. Here, we investigate the effect of an axial magnetic field on a liquid metal droplet and jet flow. A jet, which flows out from a nozzle to an ambient gas, tends to morphological instabilities. Plateau [12] has shown that due to surface tension a jet of initial radius $r_0$ may break up into parts of which the size is about the initial circumference. Physically, the break-up can be explained by the minimization of Gibbs free enthalpy. Rayleigh [13] showed that the break-up is governed by disturbances of different wavelengths. He found a minimum critical wavelength of $\lambda_c = 2\pi r_0$ for which interfacial perturbations are amplified, i.e. the cylindrical shape becomes unstable. This instability triggers the break-up of the jet into droplets. However, as shown by Chandrasekhar [14], this capillary instability might be stabilized by static magnetic fields of sufficient flux density.

In this contribution we aim to validate experimentally this stabilizing effect of a strong steady and homogeneous axial magnetic field on falling liquid metal droplets and jets. In the experiments we vary diameter and material of the nozzle, magnetic field density, the liquid metal flow rate, and the tilt angle between flow and magnetic field. The paper is organized as follows. In section 1 we present a briefly review of the dynamics of droplet and
jet flows and define the dimensionless parameters. In section 2, we present the experimental set-up. Section 3 summarizes the main results. Finally, we will provide the main conclusions.

1. Theoretical background

In this section we briefly summarize the main results of previous work [12]-[17] on the break-up of liquid metal jets into droplets. It is found that the typical droplet size corresponds to the wavelength of the most dangerous perturbation that show the highest growth rate, i.e. \( d_0 \approx 9r_0 \), where \( d_0 \) is drop diameter and \( r_0 \) is the unperturbed jet radius. It is also shown that viscous effects tend to reduce the break-up rate and increases droplet size. The break-up is a complex interplay of the effects of surface tension, inertia, and friction. These effects are parameterized by the dimensionless groups Reynolds number \( \text{Re} \), Weber number, and Ohnesorge number \( \text{Oh} \), defined by the relations

\[
\text{Re} = \frac{u_0 d}{\nu}, \quad \text{We} = \frac{\rho u_0^2 d}{\gamma}, \quad \text{Oh} = \frac{\text{Re}^{1/2}}{\text{We}}. \tag{1.1}
\]

Here, \( u_0 \) is the characteristic velocity based on mass flux and \( d \) is the characteristic length (nozzle diameter). Fluid properties are kinematic viscosity \( \nu \), density \( \rho \), and surface tension \( \gamma \). Parameters \( \text{Re} \) and \( \text{We} \) represent the ratios of inertia and friction forces and inertia and surface tension forces, respectively. Droplet flow occurs at low values of \( \text{We} \) and \( \text{Oh} \). At higher values, jet flow establishes. In this parameter range flow structures can be classified as the Rayleigh regime and first wind-induced regime, characterized by relatively small jet velocities and relatively big droplets, as well as the second wind-induced regime and atomization regime, characterized by high-speed jets and small droplets due to the growth of short-wavelength surface waves.

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 \( \text{Ha} \), and the electromagnetic interaction parameter \( N \) defined by the relations

\[
\chi = \frac{1}{4}\text{Ha}^2(l_v/r_0)^{1/2}, \quad \text{Ha} = \frac{\mu_0 d (\sigma/\rho \nu)^{1/2}}{H}, \quad N = \frac{\text{Ha}}{\text{Re}^{1/2}}. \tag{2.2}
\]

Here, \( l_v = \rho \nu^2/\gamma \) is the inherent length scale of jet break-up, \( \mu_0 \) is the flux density of the applied magnetic field, and \( \sigma \) is the electrical conductivity of the liquid. Parameters \( \text{Ha} \) and \( N \) represent the ratios of electromagnetic forces to friction forces and inertia, respectively. The main finding is that a field of sufficient strength, i.e. \( \chi > 6 \), will stabilize the jet against all perturbation wavelengths, whereby \( \lambda_c \) increases. This stabilizing effect is due to the generation of electromagnetically induced Lorentz forces within the conducting liquid. In the present case of an axial field, these Lorentz forces tend to break any flow in the radial direction. In our model experiments we expect that at high values of \( N \), the free-surface shapes of falling liquid metal jets and droplets will be strongly modified.

2. Experimental set-up

The experimental set-up is sketched in Fig. 1. A syringe pump (1) delivers the test melt GaInSn from a collecting vessel (10) to a centering device (4) at which the nozzle is fixed. Intake and outtake from and into the pump is controlled by a valve (3). Pressure is measured by a manometer (2). Centering device and nozzle are located in the middle of a superconducting DC magnet (8) which produces a homogeneous axial magnetic field up to 5 T. After its fall through the field, the melt is collected in a funnel (9). Finally, the melt flows
in a vessel (10). A high-speed camera (5) placed on top and operating at 231 fps records the projection of the jet or droplet flow on a mirror (6). Illumination is provided by a LED (7).

In the model experiments we use nozzles of three different diameters \( d = (0.9, 1.55, 2.2) \) mm and adjust flow rates in such a way to cover the parameter ranges \( \text{Re} = (340, 1690, 4500) \), \( \text{We} = (0.09, 1.9, 12.1) \), and \( \text{Oh} = (1.1 \cdot 10^{-3}, 8.8 \cdot 10^{-4}, 7.4 \cdot 10^{-4}) \). Moreover, we vary the flux density of the magnetic field according to \( B_0 = (0, 1, 2, 3, 4, 5) \) T corresponding to the parameter ranges \( 0 < \chi < 49.5 \), \( 0 < \text{Ha} < 436.4 \), and \( 0 < N < 564.4 \). Hence, our experimental set-up operates in the regime within which electromagnetic effects are predicted to stabilize jet flow. Furthermore, to investigate bending effects we apply tilt angles of \( \phi = (0, 5^\circ) \) between the axis of the field and gravity. Finally, the influence of nozzle material is studied by using either electrically non-conducting PTFE or well-conducting brass.

3. Results

3.1. Flow regimes

In our experiments, we observe three different flow regimes, depending on the Reynolds number and Weber number. For \( \text{Re} = 340 \) (\( \text{We} = 0.09 \)) droplet flow develops. Upon increasing \( \text{Re} \) up to \( \text{Re} = 1690 \) (\( \text{We} = 1.9 \)), we observe a transition from droplet flow to continuous jet flow characterized by discontinuous short-length irregular structures. At the highest Reynolds number, i.e. \( \text{Re} = 4500 \) (\( \text{We} = 12.1 \)), continuous jet flow establishes. This regime corresponds to the so-called Rayleigh regime. In the following we restrict the presentation of the results to some selected examples. A detailed discussion of all results will be given elsewhere.

3.2. Droplet formation and droplet flow at \( \text{Re} = 340 \)

Fig. 2 shows a temporal sequence of drop formation at the nozzle. Photographs are taken at the times \( t = (0, 34.7, 69.3, 103.9, 138.6, 173.2) \) ms. The upper sequence refers to the case when the magnetic field is absent, i.e. \( B_0 = 0 \). The lower sequence shows the results for \( B_0 = 5 \) T, i.e. in the presence of a strong axial magnetic field. Other parameters are \( \text{Re} = 340 \), \( d = 2.2 \) mm, and \( \phi = 0 \). We observe that the magnetic field suppresses the droplet growth in the radial direction. By that, droplets get elongated with the magnetic field lines. Similar effects are observed for all nozzle materials and diameters.

Fig. 2. Droplet formation at the nozzle for \( \text{Re} = 340 \), \( d = 2.2 \) mm, \( \phi = 0 \) at \( B_0 = 0 \) (\( \text{Ha} = 0 \)) (upper sequence) and \( B_0 = 5 \) T (\( \text{Ha} = 436.4 \)) (lower sequence)
Fig. 3 shows contours of the droplets after their detachment from the nozzle at a fixed position during their fall in the axial magnetic field. In the photographs from left to right, the field strengths are \( B_0 = (0, 1, 3, 5) \) T. Other parameters remain unchanged. A comprehensive comparison on Figs. 2 and 3 shows that after detachment, drop contours remain mainly constant. However, with increasing \( B_0 \) the droplet axis gets strictly aligned in the direction of the field and any droplet rotation, present for the case \( B_0 = 0 \) only, is suppressed. As expected, these observations are again independent of both nozzle material and nozzle diameter.

![Fig. 3. Contours of droplets after detachment. From left to right \( B_0 = (0, 1, 3, 5) \) T.](image)

### 3.3. Jet break-up at \( \text{Re} = 1690 \)

Fig. 4 shows some results from the transition regime at \( \text{Re} = 1690 \) where droplet flow turns into short-length jet flow. As before, in the photographs from left to right, the field strengths are \( B_0 = (0, 1, 3, 5) \) T and again \( d = 2.2 \) mm and \( \varphi = 0 \). We observe that under the influence of a strong axial magnetic field, the break-up of the jet and droplet formation, i.e. the so-called spherodization via capillary instabilities, are clearly suppressed. Moreover, we can conclude that the axial field tends to increase the lengths of the jets. As before, these general observations can also be made for all nozzle materials and diameters. These experimental findings clearly support the theoretical predictions [14].

![Fig. 4. Jet break-up at \( \text{Re} = 1690 \). Left to right \( B_0 = (0, 1, 3, 5) \) T.](image)

### 3.4. Jet flow at \( \text{Re} = 4500 \): influence of tilt angle and nozzle material

Fig. 5 shows results from the Rayleigh regime at \( \text{Re} = 4500 \) within which continuous jet flow establishes. In all pictures, nozzle diameter is fixed \( d = 2.2 \) mm and a strong axial magnetic field of \( B_0 = 5 \) T is present. The two left photographs depicts the case of a zero tilt angle, i.e. \( \varphi = 0 \), in the absence of a magnetic field (first picture), i.e. \( B_0 = 0 \), and in the presence of strong axial magnetic field of \( B_0 = 5 \) T (second). The two right photographs refer
Fig. 5. Jet flow at $Re = 4500$. First picture: $\varphi = 0$ and $B_0 = 0$. Second: $\varphi = 0$ and $B_0 = 5$ T. Third: $\varphi = 5^\circ$, $B_0 = 5$ T, and FTPE nozzle. Fourth: $\varphi = 5^\circ$, $B_0 = 5$ T, brass nozzle.

to the case when a slight tilt angle between the axes of magnetic field and gravity of $\varphi = 5^\circ$ and a field strength of $B_0 = 5$ T are applied. Here, the third picture refers to a nozzle made of the non-conducting material FTPE, while in fourth picture the nozzle material is electrically well-conducting brass. From our observations shown in Fig. 5 we can draw the following conclusions. For the case $\varphi = 0$, liquid metal jet flow in the Rayleigh regime is almost unaffected by an axial magnetic field and by nozzle material. This finding is due to the fact that in this regime the jet break-up may set in far downstream, i.e. at a position beyond our experimental observation range. However, when a tilt angle is applied, the electrical conductivity of nozzle material strongly influenced the dynamics of the falling jet. In case of a non-conducting nozzle, we observe that again the magnetic field does not affect the jet flow. In contrary, when the nozzle is well-conducting, the jet is bent into the direction of the magnetic field axis, i.e. aligning occurs. This aligning takes place almost completely at the nozzle exit while the downstream flow remains again almost unaffected. Hence, for the bending of the jet, Lorentz forces, generated by the interaction of induced eddy currents in the nozzle and the axial magnetic field, are responsible. Here, the strongest electromagnetic effects are acting as in this region the overall electrical resistance is lowest. In turn, inside the liquid metal jet eddy currents remain small resulting from its high electrical resistance due to its thinness.

Conclusions

We have experimentally investigated the effects of a strong axial static magnetic field on the dynamics of falling liquid metal droplets and liquid metal jets. Depending on the Reynolds number $Re$, we have detected three different flow regimes. At a low value of $Re = 340$, single droplet flow occurs. In this regime, drop formation at the nozzle exit is strongly influenced when the magnetic field is present. Furthermore, the field suppresses any droplet rotation along its fall in the field. At a medium vale of $Re = 1690$, short-length jet flow and jet break-up towards spherodization is observed. In this regime, we observe that, in accordance with theoretical predictions, the axial field strongly suppresses morphological instabilities of the jet. Finally, at a high value of $Re = 4500$, we observe the Rayleigh regime characterized by stable jet flow. In this regime the effects of the magnetic field are restricted to the cases of both a tilt angle between jet axis and field axis and electrically conducting nozzle material.
Here, induced Lorentz forces in nozzle exit region are capable to bend the jet in the direction of the field axis.

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