Fluid Flow Measurements in Electrically Driven Vortical Flows

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Abstract

Passing an electrical current through a volume of conducting fluid drives flow via the interaction with its own magnetic field. Among this class of electro-vortical flows the electrode-welding is a prominent example of industrial interest. In such configurations where a strong current is supplied locally, the resulting high current densities show phenomena like formation of jets and pinch-effect. The latter may disrupt the melt column in the case of very strong currents, accompanied by a discharge. Thus pinching can be used for a liquid metal current limiter with self-healing properties.

Local flow measurements are important for a better understanding of these phenomena. This paper gives results from a systematic study of the fluid motion performed with our mechano-optical velocity probe. The measured flow structure of the evolving jet was found to be in a reasonable agreement with our numerical simulations. Local pressure measurements have been consistent with the experimental and numerical results for the flow field.

Introduction

The present work originates from the idea of interrupting short-circuit currents in electrical power networks by means of liquid metal. The alloy In-Ga-Sn was intended to be used because it is liquid at room temperature and of its non-poisonous nature. To minimize the consequences of a severe accident the electric circuit has to be interrupted well before the first peak of the prospective current. Reaction times significantly shorter than 5 ms can be reached by liquid metal current limiters (LMCL), which accomplish this desired property by the high mobility of the switching liquid medium. Conventional short-circuit protection devices are limited to 1 to 3 interruptions by destruction due to excessive arc energy. The self-healing LMCL allows for more than 15 interruptions of heavy short-circuit currents up to 150 kAmps.

Fluid flow plays a major role in the working principle of a LMCL. As usual the design can be optimized by numerical calculations after a careful validation by experiments. Commercial techniques for the measurement of local velocities in liquid metal flows are not available, and those often used in laboratory studies fail in our physical model of the LMCL. Hence we made use of our own developed sensor [1] based on the deflection of a thin glass rod due to the flow drag, and optimized it for the present requirements. Furthermore, local pressure measurements using a commercial opto-mechanical probe were carried out for an additional validation.

1. The Liquid Metal Current Limiter

In [2] a setup is proposed that comprises a serial connection of elementary cells, in each of which an electric arc will be ignited in case of a short-circuit. A possible
implementation of such a device is shown in Fig. 1. For the electrical characteristics of such an industrial scale LMCL we refer to [3].

Starting at least from [2] until recently it was commonly accepted that the interruption of the current path is conditioned by thermal effects. The impact of heat generated by Ohm’s losses should lead to evaporation of the liquid metal. From the beginning we had severe doubts about that. Considering the huge amount of material, the high evaporation temperature, and the heat of evaporation makes obvious that the determinant effect must be something other than heat.

With no loss of generality we restrict the contemplation to one elementary cell. Each of them forces a constriction of the current path in the spacer channel. As a simple model we consider a cylindrical column carrying an axial current with a local perturbation of the column radius. At the constriction we have both an increased current density $j$, and a stronger self-magnetic field $B$, as shown in Fig. 2. This leads to an increased force density

$$ \vec{f}_{EM} = j \times \vec{B} = -\mathbf{\nabla} \cdot \left( \frac{B^2}{2\mu} \right) + \frac{1}{\mu} (\vec{B} \cdot \mathbf{\nabla}) \vec{B} $$

(1)

where $\mu$ denotes the magnetic permeability. The r.h.s. first term in (1) is a potential which is balanced by pressure and has no further consequence. The second term is rotational and leads to fluid motion. In [5] it is shown that this perturbed configuration is unstable at sufficiently high currents, with the most dangerous mode having a zero wavelength if viscosity and surface tension are neglected. This means that the column will disintegrate into very small pieces. Taking surface tension into account, this author found that the wavelength with the highest growth rate increases with the ratio between capillary and Lorentz forces. Already the results of [5] for the simple model in Fig. 2 show that fluid flow is the determining mechanism for interruption of the current path.

In the more realistic setup of the LMCL in Fig. 1 strong perturbations are present at the outset. The electric current has to converge from the full cross-section of the liquid metal through the spacer channels. In the review book [6] several examples of electrically induced vortical flows due to currents originating from a point source can be found. Whereas the formation of a jet is evident, no local velocity measurements are available, either for the jet itself or the return flow developing in closed flows. We investigated the flow field in an experimental setup sketched in Fig. 3 which resembles one elementary cell of a LMCL for an imprinted current well below
the critical value for interruption. The setup consists of a rectangular box filled with liquid metal. Massive copper electrodes form both ends. The bottom and the side walls are made from non-conducting material. A thin insulating plate in the middle between both electrodes divides the liquid metal volume. These two areas are connected by a channel with a radius of \( r_C \) drilled into the spacer. The current converging through this spacer channel is expected to deliver a large contribution to the rotational part of the force in (1) driving a strong jet directed away from the channel towards the electrodes. The right part of Fig. 3 sketches the streamlines of this torus vortex and the isolines of the resulting pressure distribution.

2. Calculation of the flow

The flow phenomena of a current carrying liquid are governed by continuity and the incompressible Navier-Stokes equations including the source term \( j \times B \) for the electromagnetic forces. The electric potential \( \phi \) can be computed from the Laplace equation, and the current density \( j \) is given by Ohm’s law (here \( \sigma \) is the electrical conductivity)

\[
\vec{\nabla} \cdot (\sigma \vec{\nabla} \phi) = 0 \quad j = \sigma (-\vec{\nabla} \phi + \vec{\nu} \times \vec{B})
\]  

The imprinted electric Field \( \vec{E} = -\vec{\nabla} \phi \) is much larger than the flow induced one, thus \( \vec{\nu} \times \vec{B} \) is neglected. Following the usual MHD approach to decouple the em equations from those of motion, we ignore the flow induced magnetic field, too. In addition, the low frequency approximation is used for the em fields based on a skin depth of the related AC magnetic field (50 or 60 Hz for power lines) being much larger than the typical size of the LMCL. The magnetic induction \( \vec{B} \) was evaluated from Biot-Savart’s law.

Because the flow is purely driven by em forces the characteristic velocity will not exceed Alfvèn’s velocity \( v_A \) based on the strength of the self-magnetic field. Taking \( v_A \) as an upper limit, the Reynolds number can be easily estimated to be \( Re \approx 1800 \) for a current of 300 Amps and the material properties of In-Ga-Sn. Due to this low Reynolds number the use of turbulence models is not appropriate in the numerical model of the LMCL.

Commercial codes which solve the eq. of fluid motion do not treat the additional MHD eq. out of the box. We employed FLUENT which we extended for the computation of the electric potential, the self-magnetic field, and the em source term by user defined routines.

The setup for the numerical model is very similar to the physical one (see Fig. 3). Besides the usual boundary conditions for the fluid flow we used zero gradient for the electric potential at insulating walls, whereas the electrode and the plane of symmetry are assumed to be iso-surfaces of the potential. Their difference is adjusted such that the desired current flows through the domain.

3. Measuring techniques

Local velocity measurements have been carried out with our mechano-optical probe (Fig. 4) which was developed during a previous study [1] to which we refer for a detailed description. The deflection of the free end of the pointer due to flow drag is monitored by a video camera from above. The displacement of the pointers image on the video frame measures the two velocity components perpendicular to the probes axis. Calibration is done via insertion of the probe into a rotating annular gap filled with the liquid under investigation rotating at pre-given angular velocities and a PC equipped with a frame grabber.

The sensitive tip of the elastic sensor has a length of 10 mm and a diameter of 50 µm only, hence it scarcely disturbs the flow. Potential difference probes mostly employed in laboratory frame for local velocity measurements cannot be used here because of the
imprinted current. The mechano-optical probe with its unexceptional electrically non-conducting parts does not suffer from this and is thus ideally suited for electro-vortical flows.

However, despite of the small size of the sensor we had to cope with the probably smaller flow structures to be expected in the LMCL. The probe is not only deflected by the velocity at the tip, but rather by a velocity profile along its sensitive part. Thus the calibration curve provides reasonable data only for a constant velocity profile. If the sensor is subjected to a strongly varying profile a systematic error occurs that cannot be compensated. This becomes more and more problematic with decreasing size of the flow structures to be measured. Therefore we developed a model of the probe to predict its response with respect to arbitrary velocity profiles. Using the profile out of a numerical simulation it is possible to obtain a virtual measurement signal which can be compared directly to the experimental results.

For the derivation of the model we treat the sensitive part as an ideal cylindrical rod fixed on one side with constant momentum of inertia $I$, elastic modulus $E$, length $l$, and diameter $D$ (Fig. 5). The area load $p(z)$ is given by the flow drag due to a local velocity profile $v(z)$

$$p(z) = 0.5 \cdot c_w(v) \cdot \rho \cdot v(z)^2 \cdot D$$  \hspace{1cm} (4)

The bending moment $M_b(z)$ due to the area load $p(z)$ is defined as

$$M_b(z) = - p(z) \text{ with } M_b(z = l) = M_b'(z = l) = 0 \hspace{1cm} (5)$$

where bending due to a longitudinal force is ignored and the prime denotes differentiation with respect to $z$. The deflection line $y(z)$ then reads

$$y''(z) = \frac{M_b(z)}{I \cdot E} \hspace{1cm} \text{with } y(z = 0) = y'(z = 0) = 0$$ \hspace{1cm} (6)

The drag coefficient $c_w(v)$ of the probe depends on the Reynolds number, and thereby in turn on the local velocity. Based on the values given in [7] we use the following fit

$$\lg(c_w) = 1.00828 - 0.66795 \lg(Re) + 0.10553 \lg(Re)^2$$ \hspace{1cm} (7)

Integrating (6) twice, the deflection $\delta = y(l)$ can be determined for a given $v(z)$ from the simulations. To compute the output signal of the virtual probe, we search for the constant area load $q$ which deflects the probe tip by the same amount

$$\delta = q \cdot l^4 \sqrt{8I \cdot E}$$ \hspace{1cm} (8)

The constant velocity $u$ which corresponds to that measured by the probe can be calculated from (4) by the insertion $p(z) = q$

$$q = 0.5 \cdot c_w(v) \cdot \rho \cdot v(z)^2 \cdot D$$ \hspace{1cm} (9)
Equations (4) to (9) can be combined into a non-linear one where the integration is to be performed over the sensor length $l$. This equation (10) can be solved numerically for the virtual probe signal $u$

$$c_w(u) \cdot u^2 = \frac{8}{\pi} \int c_w(v) \cdot v(z)^2 \, dz$$

(10)

The local pressure has been measured by a miniaturized aneroid barometer of 0.7mm in diameter made by Metricor, France. The signal consist of the interference pattern between light reflected by the end of an optical fibre, and that of a silicone crystal spaced by a bakelite hollow cylinder mounted in between.

4. Results

Prior to investigate the flow in the whole volume the sensor integration has to be validated. We measured a vertical section of the axial velocity component, directed from the spacer towards the electrode, at a distance $r_c/2$ in front of the channel for a current of 300 Amps. In Fig. 6 these experimental values are compared to the computed profile $v$ and the sensor-integrated prediction $u$.

The correspondence between the calculated maximum value of 0.66 on the line of symmetry and that of 0.28 measured by the probe is poor. Even the maximum value of the probe 0.38, found at $r/r_c=1$, is significantly smaller than the calculated one. If we compare the experiment with the integrated profile instead, the agreement is quite good. Although the maximum value in the integration is still 25% higher than the experimental one, the shape and width of the profile are predicted accurately.

For the systematic investigation we choose a width of the liquid volume of $14r_c$. By adjusting the filling level identical to the width and centering the channel with respect to the height the system is highly symmetric. Thus we restricted the experiments to a horizontal section at mid-height. The results of several discrete measurements are shown in Fig. 7, together with the computed flow field. The vortex flow is evident and the highest values of the velocity are found along the center of the jet. Over a length of at least $2r_c$ the jet is accelerated by axial Lorentz forces caused by the

Fig. 6: Comparison of a vertical profile of the axial velocity component. The velocities are made non-dimensional with respect to Alfvén’s velocity.

Fig. 7: Vortex flow in a horizontal section at mid-height. Axes are normalized with the radius of the channel. Outlined arrows are calculated in one half of the figure. The measurements were carried out in the full half-cell as can be seen from the solid arrows showing a slight asymmetry with respect to $y=0$. 
diverging current path. As it proceeds, the jet widens due to viscous effects. Close to the electrode the flow is slowed down and redirected outwards parallel to the electrode. The return flow regions are remarkably narrow.

The maximum magnetic pressure is expected in the center of the channel. Using (1) for an infinitely long cylindrical conductor of radius $R$ carrying an axial current density $j$ the potential part can be estimated as

$$p_M(r) = \frac{\mu_0 j^2}{4} \left( R^2 - r^2 \right)$$

Because an axial pressure gradient is acting as the driving force, the pressure profile from (11) is superimposed by a constant offset which is negative due to the flow outside the channel. Figure 8 shows the measured and computed radial pressure profile inside the spacer channel at the plane of symmetry (cf. Fig. 3). Both the wall pressure and parabolic shape of the profile agree very well between measurement and simulation.

Conclusion

In the present work we report results from local velocity measurements in electrically driven vortical flows and compare them to numerical simulations. To our knowledge these results are the only available measurements of adequately locally resolved velocities in this class of flows. The commonly known problems concerning flow measurements in liquid metals in general, and particularly in the case with electrical currents, could be solved by our mechano-optical probe. The combination of numerical simulation of the flow and experiments, linked by an additional numerical simulation of the sensor, allowed us to advance to experimental parameters to which we would not have any access otherwise. This strategy may be used as a valuable tool in the field of electromagnetic processing of materials.

References


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