Simulation of the Effect of a Metal Vapor Arc on Electrode Erosion in Liquid Metal Current Limiting Device

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Abstract The effect of arc plasma on electrode erosion in a liquid metal current limiter (LMCL) is studied. Based on a simplified two-dimensional magnetohydrodynamic model, the elongated GaInSn metal vapor arc and its contraction process in a liquid metal current limiter are simulated. The distributions of temperature, pressure and velocity of the arc plasma are calculated. The simulation results indicate that the electrode erosion is mainly caused by two high temperature gas jet flows arising from the pressure gradient, which is a result of the non-uniform arc temperature distribution. The gas flows, which act as jets onto the electrode surface, lead to the evaporation of the electrode material form the surface. A redesign structure of the electrode is proposed and implemented according to the analysis, which greatly increased the service life of the electrode.

Keywords: electrode erosion, GaInSn metal vapor arc, arc simulation, magnetohydrodynamic

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1 Introduction

Current limiters are used to efficiently limit the maximum amplitude of a short circuit current to reduce the thermal and mechanical stresses produced by the current. Liquid metal current limiters (LMCLs)\cite{1-4} have gained attention because of their self-response and self-healing properties, simple design without moving parts, and small volume. In this paper we study a kind of LMCL in which the short circuit current is limited by the pinch effect of fluid\cite{4}. The principle structure of this LMCL is shown in Fig. 1\cite{4}. The liquid metal partially fills an enclosure which is divided into several parts by insulating walls. The channel on each wall constricts the liquid metal and causes the self-pinch effect due to the strong non-homogeneous current density distribution and the geometrical instability of magnetic field.

Several studies on this LMCL have been conducted; KRATZSCHMAR and co-workers presented a preliminary study on the basic performance of an LMCL and some characteristics including material behavior, and made spectroscopic analysis of the electrode fall of the GaInSn arc\cite{4,5}. Refs.\cite{6-11} mainly focused on the analysis of the pre arcing liquid metal pinch phenomenon in this LMCL by formulating an analytical model. In our previous paper\cite{12}, we presented the experimental results of the arc evolution in an LMCL. During this experiment we observed the erosion on both electrodes caused by arc plasma, which seriously affects the operating life of the electrodes. However, the mechanism of the arc erosion is still not clear. Therefore, a better understanding of the effect of arc behavior on electrode erosion is of significant importance to LMCL structural optimization design.

This paper numerically studies the effect of metal vapor arc on electrode erosion in an LMCL. Supported by relevant experimental results, a preliminary two-dimensional axisymmetric MHD model of liquid metal vapor arc plasma is built. According to the calculated results, the distributions of temperature, pressure, and velocity of arc plasma are presented and fully discussed. The effect of the arc plasma on the electrode erosion is analyzed in detail.

2 Experimental result

According to the typical structure of an LMCL, the experimental device shown in Fig. 2 has been devel-
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oped. A 5 mm diameter and 10 mm length cylindrical channel, which penetrates through the insulating wall, divides the liquid metal into two parts. Part of the wall is made of acryl glass to provide a window for arc behavior observation. The liquid metal used is a nontoxic alloy GaInSn (67% Ga, 20.5% In, and 12.5% Sn by volume). An alternating current supplied by the L-C oscillation circuit is applied to the experimental device. The arc process is recorded by a digital high speed camera (Phantom V10) with 25000 pps. The images of arc initiation and evolution are obtained by using different exposure times and properly adjusting the aperture of the camera, since the intensity of image is distinctly different in these two periods.

2.1 Arc initiation and evolution

The photographs shown in Fig. 3 present the process of arc initiation. At 6.841 ms, the liquid metal free surface adjacent to the left sides of the insulating wall contracts to the bottom of the channel due to the self-pinch effect of fluid, which totally pinches off the liquid metal column in the channel; an arc ignites here and then rapidly expands in the channel. The arc initiation in the LMCL behaves just like an arc igniting in the early contact opening phase of a switchgear, and the arc at this stage should be a metal vapor arc. Moreover, during the arc expansion, the liquid metal will be heated and vaporized as it contacts the arc, which will continue to produce a mass of metal vapor. Thus, it can be concluded that the arc plasma in an LMCL should be a metal vapor arc, which is also proved by the spectral analysis result in Ref. [5]. Furthermore, it is noted that the liquid metal free surface on the left-hand side of the channel gradually rises with the expansion of the arc. This is caused by the arc pressure, which will eventually “push” the liquid metal upward to the upper space of the container.

Fig. 4 shows images of the arc evolution for the case of 3 kA current (peak value). It can be seen evidently that the arc ignites after 4.047 ms of current generation. Then the arc plasma begins to expand in the channel and lasts until 4.247 ms. Soon after the arc expansion, the liquid metal is pushed out of the channel by the arc plasma and the arc starts to elongate through the channel. The arc elongates to its maximum extent at $t \approx 5.207$ ms and the channel is full of the arc column.

Fig. 4 High-speed images of arc evolution (3 kA peak) (color online)

2.2 Arc erosion phenomenon

After repeating the same experiments mentioned above 5 times, we observe the erosion phenomenon on both electrodes in the LMCL. Fig. 5 shows photographs of the eroded electrode. Unlike the contact erosion of switch devices in air, it is noted that there is only one obvious hemispherical, smooth crater, the size of which is close to the cross section size of the channel formed on each electrode surface. The location of the crater is just opposite the channel. By analyzing the arc images, it seems that this erosion is mainly caused by the arc plasma which touches the electrodes when it elongates to its maximum extent. Although a high-speed photograph can indicate the cause of the electrode erosion, it is still insufficient for fully understanding and interpreting the inherent mechanism of this physical phenomenon.

Fig. 5 Eroded electrodes after 5 times repetition of experiments: (a) Anode, (b) Cathode (color online)
### 3 Numerical model

#### 3.1 Hypotheses

The arc model is based upon a few assumptions, as follows.

- **a.** According to the above experimental results, the electrode erosion is mainly due to the elongated arc. Because we were interested in the influence of the arc plasma on the electrode erosion rather than the detailed processes of the arc, the arc expansion and arc elongation are not modeled in this paper in order to reduce the complexity of the simulation.

- **b.** The experiment indicates that the liquid metal will be pushed upward to the upper space of the container during the arc expansion, and the channel and its ambient region are filled with the arc plasma during the arcing process, except for transitory arc initiation and arc expansion. However, the main purpose of this paper is to describe the electrode erosion resulting from the arc, especially the influence of the shape of the arc on the electrodes through the simulation, so the model mainly focuses on the arc plasma in the channel and its ambient region. Thus, the surrounding media of the elongated arc model is assumed to be GaInSn metal vapor without considering the existence of the liquid metal to reduce the complexity of the simulation. Moreover, because the channel of the LMCL is a cylinder, the model is simplified to be two dimensional and axisymmetric.

- **c.** The thermal plasma is at atmospheric and higher pressure, whose temperature is of the order of 10000 K with electron and ion number densities of about 1023 m$^{-3}$, is usually considered to be in local thermodynamic equilibrium (LTE), because of the high collision rate associated with the high pressure, which leads to the approximately equal electron and heavy particle temperatures $^{[13]}$. The GaInSn vapor arc in this study is typically at around atmospheric pressure. Its temperature is about 11700 K, as derived from the spectrum analysis reported in Ref. [5], and the electron and ion number density of the GaInSn vapor at high temperature is about 1023 m$^{-3}$, as obtained from its thermodynamic properties. Accordingly, the arc plasma is supposed to be in LTE.

- **d.** Vapors from the electrodes and the insulating wall material are not taken into account in this model.

#### 3.2 Equations

Based on the MHD theory, the mass, momentum, and energy conservation equations and the electromagnetic equations are adopted to describe the gas flow fields of the arc plasma, which are presented as follows.

**Mass conservation:**

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v) = 0. \quad (1)$$

**Momentum conservation:**

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v v) = \nabla \cdot (\eta \nabla v) - \frac{\partial p}{\partial x_i} + (J \times B). \quad (2)$$

**Energy conservation:**

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H v) - \nabla \cdot (\lambda \nabla T) = \frac{\partial q}{\partial t} + q_{\text{rad}} + \sigma E^2. \quad (3)$$

Here $t$ denotes the time; $\rho$ the density; $v$ the flow velocity; $v_i (v_r, v_z)$ the velocity component in the radial and axial direction; $x_i$ means the coordinate component in the radial and axial direction; $p$ the pressure; $B$ the magnetic field density; $J$ the current density; $\eta$ the viscosity; $H$ the enthalpy; $T$ the temperature; $q_0$ the viscous dissipation function; $q_{\text{rad}}$ the radiation energy; $\lambda$ the thermal conductivity; $c_p$ the specific heat; $\sigma$ the electrical conductivity; and $E$ the electric field.

In the above equations, the Lorentz force density $J \times B$ is involved in the momentum source term, and the source term of the energy conservation equation includes the Joule heat $\sigma E^2$, radiation energy $q_{\text{rad}}$, and viscous dissipation $q_0$. In this study, $q_{\text{rad}}$ is obtained from Ref. [14] as

$$q_{\text{rad}} = 4\alpha k(T^4 - T_0^4), \quad (4)$$

where $\alpha = 5.67057 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$ is a constant, $k$ is the absorption coefficient, $T$ is the temperature, and $T_0=300$ K is the ambient temperature.

The magnetic field and the electrical potential are calculated in the whole computation domain. The potential vector $A$ is adopted to calculate the electromagnetic field:

$$\nabla \cdot (\nabla A) = -\mu_0 J, \quad (5)$$

$$B = \nabla \times A. \quad (6)$$

The electrical potential and the current density are calculated by:

$$\nabla \cdot (\sigma \nabla \phi) = 0, \quad (7)$$

$$E = -\nabla \phi, \quad (8)$$

$$J = \sigma E, \quad (9)$$

where $A$ is the potential vector, $\phi$ the electric potential, and $\mu_0$ the vacuum permeability.

The transport and thermodynamic properties ($\sigma, \rho, \eta, c_P, \lambda$) of the GaInSn metal vapor arc given above vary with the temperature and pressure. The thermodynamic properties can be calculated by the equilibrium composition of the arc plasma in LTE, which is obtained by using the method of minimization of the Gibbs energy $^{[13,15,16]}$, and the transport properties can be calculated by the solution of Boltzmann’s integro-differential equation using the well-known Chapman-Enskog method $^{[13,16]}$. The properties of the GaInSn vapor used in this paper are provided by A. B. MURPHY. The electrical conductivities, viscosity, and thermal conductivities of the GaInSn metal vapor for different pressures and temperatures are shown in Figs. 6~8, respectively.
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Fig. 6  Electrical conductivities versus temperature for different pressures

Fig. 7  Viscosity versus temperature for different pressures

Fig. 8  Thermal conductivities versus temperature for different pressures

3.3 Geometric and boundary conditions

As shown in Fig. 9, a simplified 2D axisymmetric model is proposed based on the LMCL experimental setup shown in Fig. 2. The dimension of the geometry is $R_1=10\text{ mm} \times 18\text{ mm}$ in the radial $r$ and axial $z$ direction, respectively, with one channel of dimension $R_2=2.5\text{ mm} \times 10\text{ mm}$ on the insulating wall. The fluid domain is enclosed by an electrode and sidewalls filled with GaInSn vapor. The grid sizes of the model are set to be $0.25\text{ mm}$ and $0.3\text{ mm}$ in the $r$ and $z$ directions, respectively, and the total number of cells is about 10560.

Following the routine adopted in Fluent computation, a no-slip boundary condition is enforced on the wall-plasma interfaces \cite{17\textendash}19. A constant temperature of $2500\text{ K}$ is set as the boundary condition of temperature on the electrode \cite{20}. The temperatures at the insulating walls and side walls are set to $300\text{ K}$. To calculate the electric potential distribution, electric boundary conditions are defined as follows: $\phi=0$ on the surface of the cathode and a uniform current density $j$ is set on the current inlet of the anode, as shown in Fig. 5.

$$j = I/S,$$  \hspace{1cm} (10)

where $I$ is the total current and $S$ is the area of the current inlet.

The boundary condition of the magnetic potential vector is set to zero at a large distance away from the model according to the fact that the magnetic field decreases as $1/r^2$ ($r$ is the distance from the current source).

4 Simulation and analysis

Based on the equations and boundary conditions described above, a coupled solver of Fluent is used for the calculation and the numerical scheme is implicit in time with the time step size set to $2\mu\text{s}$ in the transient solution.

During the simulation, the initial state of the arc is taken from the stationary simulation results, which are calculated first. The alternating current value used in the calculation is derived from the experimental data aforementioned. For the stationary calculation, the current is set to $1.4\text{ kA}$ corresponding to the elongated arc at $5.207\text{ ms}$ shown in Fig. 4.

The temperature distribution of the arc plasma at different instants is presented in Fig. 10. The simulation result at $t=0\text{ ms}$ corresponds to the experimental result at $t=5.207\text{ ms}$ shown in Fig. 4. Each frame of Fig. 10 shows that the arc is constricted by the channel and the maximal temperature region is located in the channel. The temperature of arc plasma at both sides of the channel gradually decreases along the axis direction. This temperature distribution is caused by the non-uniform current density distribution due to the shrinkage-spread structure of the LMCL, and leads to a dumbbell-shaped arc column between the electrodes. Such a phenomenon is similar to the experimental results shown in Fig. 4. From $0\text{ ms}$ to $0.72\text{ ms}$, the arc column gradually shrinks into the channel with the decrease of arc temperature. This tendency of the arc evolution is consistent with the result form $t=5.207\text{ ms}$ to $t=5.927\text{ ms}$. The two facts mentioned above indicate that the method used in the present simulation work seems reasonable and feasible.

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From the pressure field distribution at $t=0$ ms shown in Fig. 11, it can be seen that a great pressure gradient is formed because of the non-uniform arc temperature distribution described above. Fig. 12 shows the velocity field of the GaInSn metal vapor arc at $t=0$ ms. Two jet flows are formed at both sides of the channel, as shown in Fig. 12(a), due to the pressure gradient. From Fig. 12(b), it can be seen that the high speed region of the high temperature gas flow is distributed around the central axial of the channel, the width of which is approximately equal to the diameter of the channel. The flow injects onto the electrode surface along the axis direction.

These simulation results can be used to explain the formation of the round erosion on the two electrodes as mentioned above. When the high temperature gas flow arising from the pressure gradient is injected onto the electrode surfaces, the electrode surface material is evaporated by the strong gas stream of the arc plasma, which leads to the formation of craters on the electrodes. In addition, the width of the gas flow high speed region results in a crater size similar to the channel diameter.

We redesigned the electrode structure according to the above analysis. Two non-conductive ceramic disks were mounted on the inner surface of the electrode. As shown in Fig. 13, the disks are located opposite the channels of the adjacent partition walls to prevent them from the impact of the high temperature arc gas flow. The equivalent resistance of a LMCL with 6 channels was measured by using a double bridge before and after the fitting of the ceramic disk. The resistances without and with the ceramic disk are 1.476 mΩ and 1.505 mΩ, respectively, which indicates that the ceramic disk has little influence on the equivalent resistance. From Fig. 14, it can be seen that there is no arc erosion trace on the electrode after repeated experiments, and thus this renovation did greatly increase the service life of the electrode.
Supported by experiments, the elongated GaInSn metal vapor arc and its contraction process in a liquid metal current limiter were numerically studied based on the MHD theory. The simulation results reveal the arc erosion mechanism on electrodes. It indicates that two high temperature jet flows are formed on both sides of the channel due to the pressure gradient, which is a result of the non-uniform arc temperature distribution. The electrode erosion is mainly caused by these two high temperature gas flows, which act as jets on the electrode surface and leads to the evaporation of the electrode material form the surface. The high speed region dimension of the gas flow leads to a crater size similar to the channel diameter. A redesign is proposed according to the analysis, which greatly increased the service life of the electrode.

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References

5 Berger F, Duhr O, Kratzschmar A, et al. 2001, Physical effect and arc characteristics of liquid metal current limiters. Presented at the 9th Int. Conf. on switching arc phenomena, Lodz, Poland
11 Wu Huaren, Li Xiaohui, Zhang Min, et al. 2006, Analysis and design of GaInSn current limiter. Presented at 41st IAS annual meeting, Florida, USA

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