Numerical Simulation of Low Current Vacuum Arc Supersonic Flow*

WANG Lijun (王立军), JIA Shenli (贾申利), SHI Zongqian (史宗谦),
ZHANG Ling (张玲), RONG Mingzhe (荣命哲)

State Key Laboratory of Electrical Insulation and Power Equipment,
Xi'an Jiaotong University, Xi'an 710049, China

Abstract Based on a two-dimensional axisymmetric magneto-hydrodynamic (MHD) model, low current vacuum arc (LCVA) characteristics are studied. The influence of cathode process under different axial magnetic fields and different anode radii on LCVA characteristics is also simulated. The results show that the influence of both cathode process and anode radii on LCVA is significant. The sign of anode sheath potentials can change from negative to positive with the decrease of anode radii. The simulation results are in part verified by experimental results. Especially, as the effect of ion kinetic energy is considered, ion temperature is improved significantly; which is in agreement with experimental results.

Keywords: low current vacuum arc, model, simulation

PACS: *52.80.Vp, 52.80.Mg*

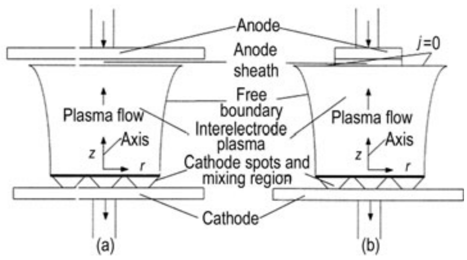
1 Introduction

Vacuum arc has been widely used in many fields, such as vacuum interrupter [1], vacuum arc coating [2], ion implantation [3,4], metal remelting [5], and so on. Characteristics of LCVA were significantly different from that of higher current vacuum arc.

Because of the complexity of vacuum arc, many plasma parameters cannot be directly acquired by experiments. So, numerical simulation of vacuum arc is one of the effective tools for the study of vacuum arc. At present, some researchers have proposed several kinds of vacuum arc models. The typical models were proposed by BOXMAN [6], KEIDAR and BEILIS [7,8], as well as SCHADE and SHMELEV [9].

Previously, the constricted vacuum arc (with high arc current) was simulated and analyzed [10], and simultaneously, the influence of different distributed axial magnetic fields (AMFs) and cathode spots distribution on constricted vacuum arc was also analyzed [11]. In this paper, we will study LCVA, first study fundamental characteristics, and then study the influence of cathode process and different anode radii on LCVA characteristics.

This paper is organized as follows. In Section 2, we introduce the model for LCVA. In Section 3, we present the simulation results and the comparison between simulation results and experimental ones. In Section 4, we will discuss and analyze the simulation results. Finally, conclusions of this paper will be drawn.



(a) Anode is large enough; (b) Anode is small
Fig.1 Schematic model

2 LCVA model

A schematic model of LCVA is shown in Fig. 1. In this model, we divide LCVA into three regions, namely cathode spots region, interelectrode plasma region and anode sheath region. When the arc current is not large enough, interelectrode plasma is mainly supplied by cathode spots. The direction of plasma flow is from cathode to anode. Electrons and ions are the carriers of arc current. Because the relaxation of plasma is fast enough compared to power frequency current, the LCVA is considered to be in a quasi-steady state in the model. Therefore, LCVA model with fixed gap distance and fixed current is calculated and analyzed in this paper. MHD model is adopted in the simulation. Detailed mathematical model can be found in Ref. [11]. When the anode is large enough, it is regarded as the collector of plasma and when anode is small, some plasma will lose at anode side, the current density outside anode is assumed to be zero.

*supported by National Natural Science Foundation of China (No. 50537050) and the Innovation Foundation of State Key Laboratory of Electrical Insulation and Power Equipment

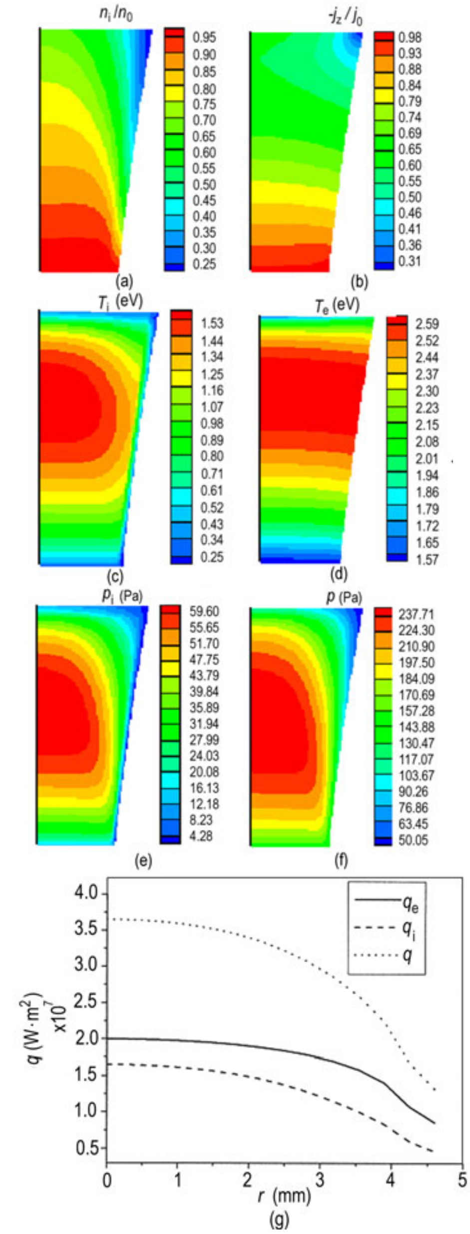
3 Simulation results

In this section, we will give the simulation results. At first, the fundamental characteristics of LCVA are studied, and then, the influence of different anode radii on LCVA characteristics will be studied.

3.1 Fundamental characteristics of LCVA

In this subsection, arc current is set to be 100 A, electrode gap is set to be 10 mm, and initial jet angle is set to be 5°, AMF is not considered, i.e., $B_z = 0$. The results on the fundamental characteristics of LCVA are shown in Fig. 2. In Fig. 2(a)∼(g), the upper side is anode the lower side is cathode, the left side is arc center and the right side is free boundary. From Fig. 2, it can be found that LCVA is in a diffusion status, ion number density and axial current density along jet axis decrease from cathode to anode. In Fig. 2, n_0 and j_0 are ion number density, current density of cathode side respectively. Ion velocity firstly decreases, and then increases from cathode side to anode side, but not significantly. Simultaneously, it can also be found that ion temperature and electron temperature firstly increase, and then decrease significantly from cathode side to anode side. For LCVA, ion temperature is always lower than electron temperature. The plasma pressure includes both ion pressure and electron pressure.

From Fig. 2, we can also find that the variation trend of ion temperature is similar to that of ion pressure, which is because the change of ion temperature is more significant than that of ion density. According to Dalton law ($P = nkT$), ion pressure also firstly increases, and then decreases significantly from cathode side to anode side. By numerical simulation, the heat flux density to anode q can be calculated according to BOXMAN's model [12] and is shown in Fig. 2(g). The heat flux density to anode includes the contributions from both electrons and ions.



(a) ion number density; (b) axial current density; (c) ion temperature; (d) electron temperature; (e) ion pressure; (f) plasma pressure; (g) heat flux density to anode (Ra: radius of anode side)

Fig.2 Fundamental characteristics of LCVA

3.2 Influence of cathode process on LCVA

According to MORIMIYA's experimental results on LCVA [16], with the increase of AMF strength, the radii at cathode side will decrease significantly. Here, we study the effect of different AMFs on LCVA characteristics according to the experimental results (with consideration of cathode side radii). The heat flux density to anode is shown in Fig. 3.

In the simulation, arc current is set to be 80 A; AMF is set to be 40 mT, 80 mT and 120 mT respectively. Results show that the influence of cathode process on LCVA characteristics is significant, similar to that in high current vacuum arc [11]. Results also show that arc voltage increases with the increase of AMF strength, which is also in agreement with MORIMIYA's experimental results.

3.3 The influence of anode radii on LCVA characteristics

According to KIMBLIN's experimental results [17], for a smaller anode radius, anode spots begin to appear at an arc current of about 450 A with a cathode radius of 25 mm, an electrode separation of 25 mm, an

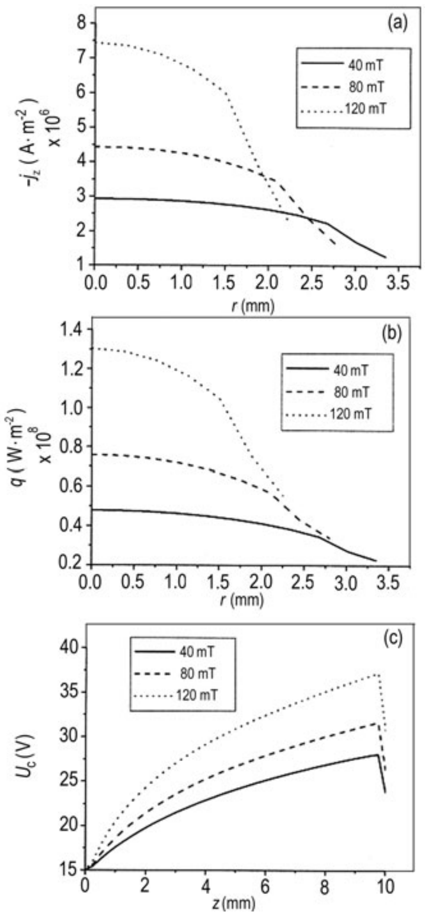


Fig.3 Influence of cathode process under different AMFs on LCVA characteristics

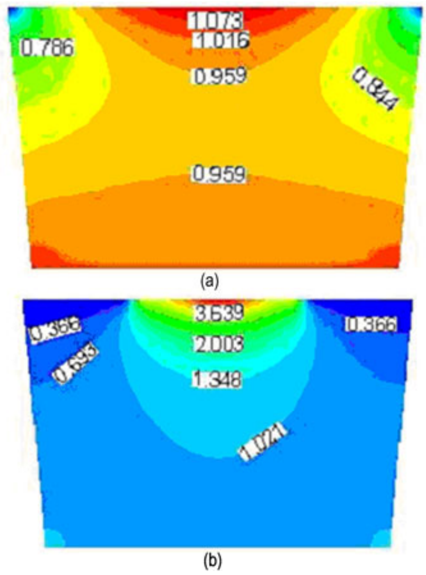


Fig.4 Distribution of axial current density with different anode radii of (a) 8 mm and (b) 4 mm

anode radius of 6.5 mm but without external AMF. DYUZHEV et al [18] deem that appearance of anode spots is related to the sign change of anode sheath potentials. So, in this paper, we study the influence of anode radii on sign change of anode sheath potentials and appearance of anode spots. In the simulation, the cathode side radius is set to be 7 mm while the anode radius is set to be 3 mm, 4 mm and 8 mm respectively, while the electrode separation is set to be 10 mm. The distribution of axial current density with different anode radii is shown in Fig. 4. Results show that current density of anode side at arc center increases significantly with the decrease of anode radii. When the anode radius is small enough, electron current density of anode side at arc center can be higher than random electron current density, the sign of anode sheath potential will change from negative to positive. This will lead to the instability of arc burning and the appearance of anode spots.

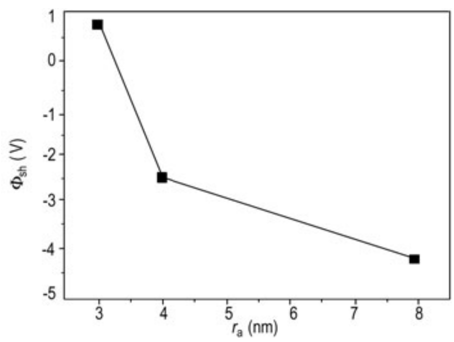


Fig.5 Influence of anode radii on anode sheath potentials

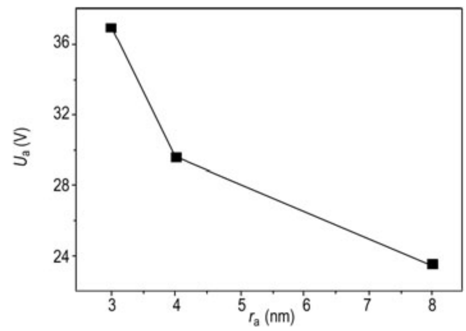


Fig.6 Influence of anode radii on arc voltages

Fig. 5 and Fig. 6 show that the influence of anode radii on anode sheath potentials and arc voltages. Simulation results show that arc voltage increases significantly with the decrease of anode radii. Sign change of the anode sheath potentials occurs when anode radius is 3 mm. The significant increase of arc voltage is also related to the loss of plasma, which is also verified experimentally [19].

3.4 Comparisons between simulation results and experimental results

In order to validate the model and results, we observe LCVA appearance in the detachable vacuum chamber with a minimal pressure: of 10^{-4} Pa through high speed CCD camera. The comparison of simulation results and experimental ones is shown in Fig. 7.

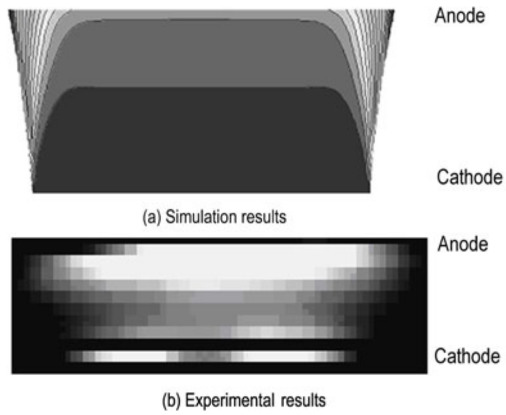


Fig.7 Comparison between simulation and experimental results

According to the comparison, it can be found that the simulation results is similar to that from CCD photograph. Simultaneously, we also measure arc voltage through high voltage probe. The experimental result of arc voltage is about 21 V, and simulation result of arc voltage is about 20.5 V. The simulated arc voltage is the plasma potential along jet axis. Therefore, simulation result of arc voltage is also in good agreement with experimental result of arc voltage.

According to LUNEV et al [20] and DAVIS and MILLER's experiments for Cu and Mo vacuum arc [21], ion temperature is about 3 eV. A comparisons between the simulation results and experimental results on ion temperature is listed in Table 1. The comparison shows that the previous simulation results [7,8,22] are much lower than the experimental results. But the result of this paper is in a reasonable agreement with experimental result, which is mainly because that the influence of ion kinetic energy is considered. Of course, due to the complexity of vacuum arc, the strict conformity is very difficult.

Table 1. Experimental and simulation results of ion temperature (in eV)

Experimental results	[7][8]	[22]	This paper
3	0.3	<0.5	≈ 2

According to GALONSKA et al's experimental results [23], with the increase of AMF strength, electron temperature increases; which is also in agreement with our simulation results.

4 Discussions

When the arc current is lower, pinch force, generated by axial current density and azimuthal magnetic field, is also lower. Simultaneously, pressure gradient will make vacuum arc diffusing along radial direction. Therefore, LCVA is in a diffusive status. Just because the LCVA is diffusive, from cathode to anode, ion number density and axial current density along jet axis decrease from cathode to anode. As there exists azimuthal magnetic field, ion velocity will firstly decrease, and then increase from cathode to anode, but the variation of ion velocity is not significant from cathode to anode. As ion of LCVA is in the hypersonic status, a small variation of ion velocity can lead to a significant variation of ion temperature. From above simulation results, we can find that the ion temperature increases from 0.3 eV (cathode side) to about 1.6 eV (near anode side). This significant increase of ion temperature is intimately related to the ion kinetic energy terms in ion energy conservation equation.

Electron temperature firstly increases, and then decreases from cathode to anode. The increase is due to joule heating, and the decrease is because that the electrons consume their energy when they cross over anode sheath and attain to anode.

For different anode radii, with the decease of anode radii, current density of anode side in arc center will increase of significantly. This will lead to the sign change of anode sheath potentials.

5 Conclusions

Through numerical simulation of LCVA, we can draw the following conclusions:

a. The influence of Hall effect on LCVA characteristics is not so significant as for higher current vacuum arc, and the influence of free boundary positions on LCVA characteristics is significant;

b. The influence of cathode process on LCVA characteristics is significant;

c. The sign of anode sheath potential can turn from negative to positive with the decrease of anode radii;

d. Because the influence of ion kinetic energy is considered, ion temperature is improved significantly, which is in agreement with experiments.

References

1 Yanabu S, Sohma S, Tamagawa T, et al. 1979, Proc. Inst. Elec. Eng., 126: 313
2 Boxman R L, Beilis I I, Gidalevich E, et al. 2005, IEEE Trans. Plasma Sci., 33: 1618
3 Keidar M, Monteiro O R, Anders A, et al. 2002, Appl. Phys. Letter, 81: 1183
4 Keidar M, Beilis I I. 1999, Plasma Sources Sci. Technol., 8: 376
5 Chaelle P, Bellot J P, Duval H, et al. 2002, J. Phys. D, Appl. Phys., 35: 137
6 Boxman R L. 1977, J. App. Phys., 48: 2338

7 Keidar M, Beilis I I, Boxman R L, et al. 1996, J. Phys. D: Appl Phys., 29: 1973

8 Beilis I I, Keidar M, Boxman R L, et al. 1998, J. Appl. Phy., 83: 709

9 Schade E, Shmelev D L. 2003 IEEE Trans. Plasma Sci., 31: 890

10 Wang L, Jia S, Shi Z, et al. 2005, Plasma Sci. Technol., 7: 2686

11 Wang L, Jia S, Shi Z, et al. 2005, J. Phys. D, Appl. Phys., 38: 1034

12 Boxman R L, Goldsmith S. 1983, J. App. Phys., 54: 592

13 Beilis I I. 2001, IEEE Trans. Plasma Sci., 29: 657

14 Gundlach H C W. 1978, Proc. 8th Int. Symp. on Discharges and Insulation in Vacuum, (Albuquerque, NM, 1978). p.A2-1

15 Sherman J C, Webster R, Jenkins J E, et al. 1978, J. Phys. D: Appl. Phys., 11: 379

16 Morimiya O, Sohma S, Sugawara T, et al. 1973, IEEE Trans. Power Appar. Syst., 92: 1723

17 Kimblin C W. 1971, Proceeding of IEEE. 59: 546

18 Dyuzhev G A, Lyubimov G A, Shkol'nik S M. 1983, IEEE Trans. Plasma Sci., 11: 36

19 Chaly A, Logachev A, Shkol'nik S. 1999, IEEE Trans. Plasma Sci., 27: 827

20 Lunev V M, Ovcharenko V D, Khoroshikh V M. 1977, Sov. Phys. Tech. Phys., 22: 855

21 Davis W D, Miller H C. 1969, J. Appl. Phys., 40: 2212

22 Shmelev D L. 2004, Proc. 11th Int. Symp. on Discharges and Insulation in Vacuum, (Yalta, Ukraine, 2004). p.411

23 Galonska M, Hollinger R, Krinberg I A, et al. 2004, Proc. 11th Int. Symp. on Discharges and Insulation in Vacuum, (Yalta, Ukraine, 2004). p.209

(Manuscript received 5 June 2007)
E-mail address of WANG Lijun:
lijunwang@mail.xjtu.edu.cn