Investigation on Plasma Jet Flow Phenomena During DC Air Arc Motion in Bridge-Type Contacts*

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Abstract Arc plasma jet flow in the air was investigated under a bridge-type contacts in a DC 270 V resistive circuit. We characterized the arc plasma jet flow appearance at different currents by using high-speed photography, and two polished contacts were used to search for the relationship between roughness and plasma jet flow. Then, to make the nature of arc plasma jet flow phenomena clear, a simplified model based on magnetohydrodynamic (MHD) theory was established and calculated. The simulated DC arc plasma was presented with the temperature distribution and the current density distribution. Furthermore, the calculated arc flow velocity field showed that the circular vortex was an embodiment of the arc plasma jet flow progress. The combined action of volume force and contact surface was the main reason of the arc jet flow.

Keywords: arc plasma, jet flow, arc model, resistive load

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(Some figures may appear in colour only in the online journal)

1 Introduction

Arc plasma jet flow is a hot ionized gas and often with metal vapor. On one hand, it is the disadvantage for the extinguishing of the arc in the switch apparatus, on the other hand, it erodes the contacts material seriously. As is well known, when the current was over 30-50 A, the directional flows of hot gas particles and metal vapor were discovered in the arc channel through a high speed shoot. Normally, this directional flow was an outflow from the shrink part of the arc channel near the electrode. The near-contact zone high temperature arc column and the corresponding higher pressure are the major factors of the formation of arc plasma jet flow, at the same time it promotes the progress of arc plasma jet flow that the self magnetic field is produced by the arc. The parameters of the arc plasma jet flow, such as length, diameter and particle front-line distribution depend on current and contacts material.

Maecker reported that in the zone between the arc column and arc root, the gradient of axis pressure causes an electrode jet flow, which is due to the different contraction of self hysteresis [1]. The velocity of the arc plasma jet flow at the electrode surface was obtained by the vapor expansion of electrode material [2]. In Ref. [3], Yi Wu et al. reported that a "bulge" (or which was also called the "nose") and a tail behind the arc column with temperatures of several thousand kelvins, it was due to the turned forward direction of jets under the function of the magnetic force on the motion of an air arc plasma.

In this paper, characteristics of the DC air arc plasma jet flow with bridge-type contacts are investigated, particularly the current and the roughness of Cu contacts surface. Firstly, according to different currents and the different contact surface roughness, the characteristics of the arc plasma jet flow were investigated. Secondly, the numerical simulation of the arc was studied. Finally, the formation of the arc plasma jet flow was discussed.

2 Experimental setup

To acquire the general characteristics of the arc plasma jet flow, experiments have to be carried out. The experimental circuit is shown in Fig. 1. A bistable electromagnet mechanism based on a permanent magnet solenoid to simulate the high-speed to open the contacts which is the same as a certain type relay product [4,5]. The DC power supply is generated by a switch-type power source TN-KGZ01 (0-1000 V), R is a variable resistor that is compose of multiple 0.675 Ω/60 kW constantan resistance, and its inductance is less than 10 μH. The arc voltage and current are measured by an oscilloscope Agilent DSO-X3024A with two channels. One channel is connected to a high-voltage probe AgilentN2863B to obtain the voltage signal and the other channel is connected to a Tektronix TCP300 amplifier AC/DC current probe

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through a current transformer KT500A. The picture of the real bridge-type contacts is shown in Fig. 2(a), and its shooting angle is along the x axis in Fig. 2(b). The two static contacts are cylinders and the moving contact is a rectangle. A transverse magnetic field which is provided by a NdFeB permanent magnet is applied to blow out the arc, and its direction points outside along the z axis as shown in Fig. 2(b). All the common experimental conditions are shown in Table 1; current varies from 50 A to 200 A. The material of the contacts is Cu. The contacts surfaces were polished by using 2000# and 100# sand paper, which represent the varying degrees of contacts roughness, then the contacts were degreased using alcohol and distilled water in an ultrasonic cleaner, then dried and carefully mounted in the test apparatus. Each condition was carried out in 15 experiments.

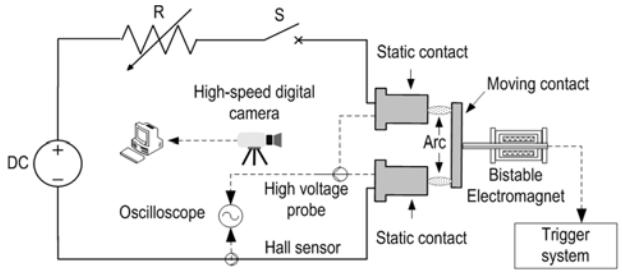

Fig.1 Schematic diagram of the experimental system

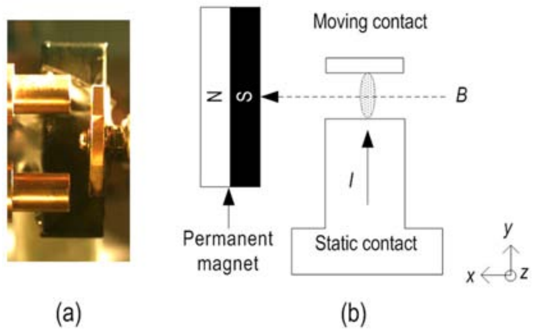

Fig.2 The bridge-type contacts and magnetic field

Table 1. Experimental conditions

Parameters	Value
Voltage	270 V
Current	50 A, 100 A, 200 A
Resistant	5.4 Ω, 2.7 Ω, 1.35 Ω
Transverse magnetic field	50 mT
Separation speed	1.1 m/s

The images of arc plasma are recorded by a Phantom V7.3 high-speed digital camera with a speed of 100000 frames/s and an exposure time of 47 μs recording the arc appearance.

3 Experimental results

The normal break arc is shown in Fig. 3. The Lorentz force provided by the transverse magnetic field drives the arc plasma column. The outline of the arc column is a regular curve, and the color of the arc is pale green. This phenomenon can be observed when the surfaces of new contacts are heated and cleaned several times by ion bombardment of the arc, especially short arcs. During those arcs, the metal burr and impurity on the contact surface were detonated by the effect of the high temperature arc plasma. At some levels, it is just as the effect of spark conditioning of HV vacuum interrupters.

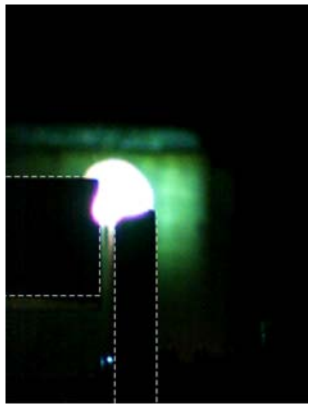

Fig.3 The normal break arc

The number of arc jet flow appearing under each set of experimental conditions is shown in Fig. 4. When the current is 50 A, the number of arc jet flow appeared with the contacts, which were polished by 2000# sand paper, and 100# sand paper which are 1 and 4 respectively, when the current is 200 A, the number of arc jet flow appearing is 9 and 13 respectively, the probability increased by 60% approximately.

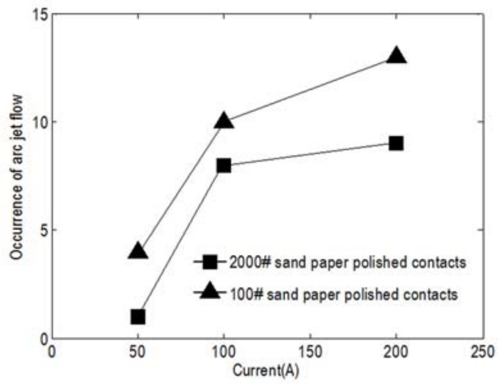

Fig.4 Occurrence of arc jet flow in 15 experiments

The arc images recorded by high-speed camera are shown in Fig. 5, the experiments are carried out under contacts with different surfaces and different currents, only the images of the arc plasma jet flow are presented.

After the arc plasma jet flow appears, the color of the arc is purplish red. The outline of the arc column is a “flame” shape, not a regular curve. It is difficult to regulate and control the arc through a magnetic field that the plasma jet flow has already appeared in. A great quantity of hot metal vapors is shot out by the plasma jet flow and more metal particles participate in the transmission process of internal arc plasma. The length of arc plasma jet flow which was generated between contacts polished by 2000# sand paper, is shorter than the length of the arc plasma jet flow which was polished by 100#, as shown in Fig. 5. The surface roughness of the contacts which were polished by 100# sand paper is more coarse and uneven than the contacts surface polished by 2000# sand paper, therefore, it is easy to generate a molten bridge. Then the more the molten bridge is vaporizing even an explosion, a great quantity of hot mental vapors comes into being. To this extent, improving the material surface treatment process and reducing the material surface roughness after arc erosion help to decrease the risk of serious arc plasma jet flow.

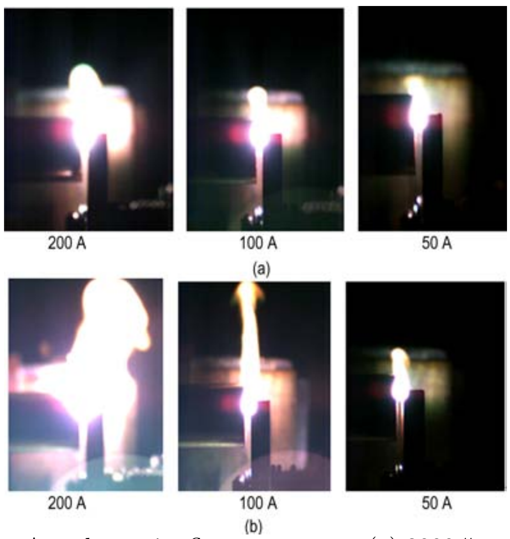

Fig.5 Arc plasma jet flow appearance (a) 2000# sand paper polished contacts, (b) 100# sand paper polished contacts

It is to increase the arc duration time that was influenced by the plasma jet flow as shown in Fig. 6. With the current amplifying, the arc plasma jet flow becomes severe. On one hand, high current will let more quantity of heat pour into the arc gap. More quantity of heat, more vaporization of electrode material, on the other hand, the inherent magnetic field of the arc column, which is increased due to the current increasing, becomes so strong that it will lead to greater contraction pressure

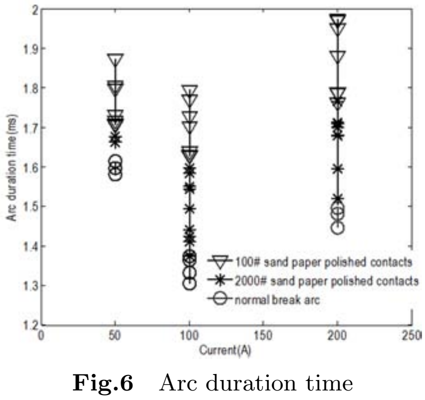

Fig.6 Arc duration time

4 Numerical simulation

4.1 Government equations

The main task in this part is to acquire the internal parameters of the arc plasma. The numerical model is established based on MHD theory, which has been widely used for investigating the arc characteristics [7−14]. The conservation laws of compressible gas are described by a mass continuity equation, the Navier-Stokes equations and an energy conservation equation, which are written as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0, \tag{1}$$

$$\frac{\partial \rho \upsilon_i}{\partial t} + \nabla \cdot (\rho \upsilon_i \vec{V}) = -\nabla p - \nabla \cdot (\eta \nabla \upsilon_i) + \vec{J} \times \vec{B}, \tag{2}$$

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \vec{V}) = -\nabla \cdot (\frac{\lambda}{c_p} \nabla h) + S_h, \tag{3}$$

where, ρ is the density, t is time, $\vec{V}$ is the velocity vector, υ_i is the velocity component, $\vec{J}$ is the current density, $\vec{B}$ is the total magnetic density, c_p is the specific heat, λ is the thermal conductivity, P is pressure, h is the enthalpy, η is the dynamic viscosity, and S_h is the enthalpy source term of energy conservation. The electromagnetic field is described by the following Maxwell equations:

$$\vec{J} = \sigma \vec{E}, \tag{4}$$

$$\vec{E} = -\nabla \varphi, \tag{5}$$

$$\vec{B} = \nabla \times \vec{A}, \tag{6}$$

$\vec{E}$ is the electrical field intensity, σ is the electrical conductivity, and φ is the electric potential. The air plasma physical properties σ, λ, η, c_p and ρ depend on temperature and pressure [6−14].

4.2 Simplifications and boundary conditions

To reduce the complexity of the simulation, a 1/2 symmetric model is established. A few assumptions and simplifications are adopted as follows: plasma is in a state of local thermodynamic equilibrium, arc ignition and extinction are not included in the simulation, the effect of metal vapor is not considered in the simulation to reduce the complexity of the research work, and the eddy current in the arc and contacts part is also not included in this model. The calculation begins with an initial arc which is imposed between the contacts as shown in Fig. 7 with a stationary temperature distribution of 10000 K. A no-slip boundary condition is imposed on the wall/plasma interfaces. All the outside boundaries of the sidewall have a temperature 300 K and a pressure atmosphere. The moving mesh is used to deal with the moving contacts during the simulation, the average speed of the moving contact is 1.1 m/s, and it is the same as the experimental condition of the experimental setup part. An electrical circuit which is the same as the experiment is coupled with the arc plasma magnetohydrodynamics model [16], the DC power is 270 V, the resistance is 1.35 Ω, and the current is 200 A.

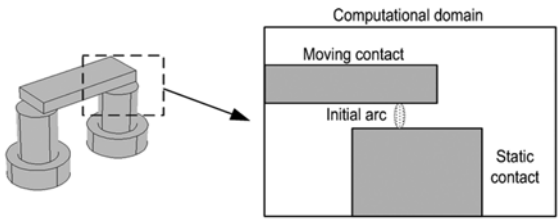

Fig.7 Schematic of the contacts adopted in the simulation

In addition, the coupled equations mentioned above are solved by the package of commercial software COMSOL-Multiphysics.

4.3 Simulation results and discussion

Fig. 8 shows the temperature distribution in the symmetric plane at 0.2 ms when the moment of the arc plasma jet flow appears obviously; to make the figure clearer, only those regions with a temperature higher than 3000 K are shown. A “flame” is visible in front of the arc column, the middle part of the arc column is elongated, and the temperature of the plasma jet flow part is high relatively.

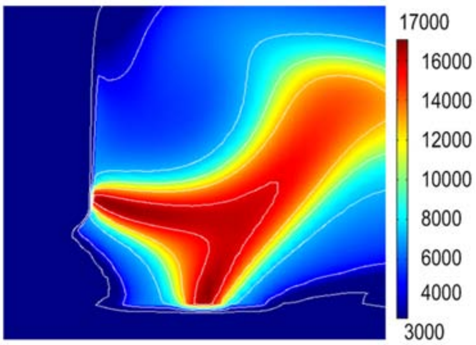

Fig.8 Arc temperature distribution (K)

Fig. 9 shows the arc current density, the current density of the plasma jet flow part is smaller than the arc column, the flow velocity is higher under the continuous effect of magnetic force and flow field, the thermal hysteresis will let the electrical conductivity of the jet flow part remain low for some time.

The flow velocity field in the symmetric plane at 0.2 ms is shown in Fig. 10(a). The volume force in the symmetric plane at 0.2 ms is shown in Fig. 10(b). It is notable that two major gas flows hit the middle of the jet flow part of the axis of the symmetry plane. A circular vortex near the contacts is obvious. In this phase, the gas flow velocity near the arc root is mainly along the vertical direction, which promotes the hot gas energy to be transported to the area ahead of the arc column. Due to the contraction zone of near contact with high temperature and high vapor pressure, combining the action of magnetic forces and gas dynamics, all of these form the volume force. A great quantity of metal particles is sprayed out by the impact of the volume force, especially when there is metal burr, swarf, adsorption gas or even oxidation film etc. near or in the arc root.

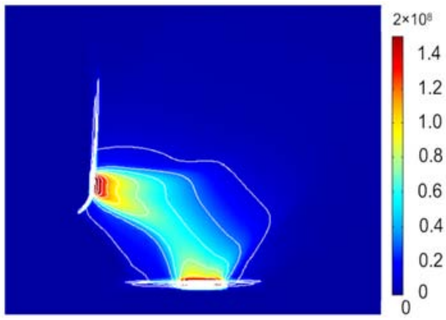

Fig.9 Arc current density (A/m^2)

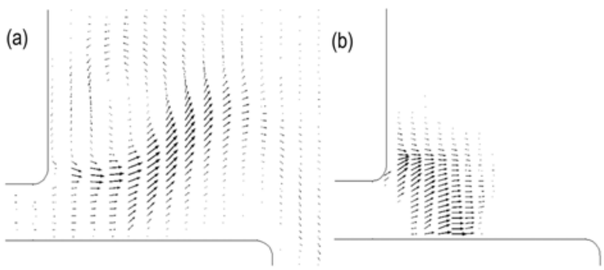

Fig.10 Flow velocity field (a) and volume force (b) distributions

5 Conclusions

The arc plasma jet flow in a typical air bridge-type contact is investigated through experiments and simulations in this paper. The phenomenon of arc plasma jet flow is revealed and analyzed in detail. The influences of current and the surface roughness of Cu contacts are researched, and we have reached the following conclusions.

a. The roughness of the contacts surface plays an important role in the formation of an arc plasma jet flow, the rough surface is apt to take the shape of serious arc plasma jet flow.

b. The number of arc plasma jet flows appearing goes up with the increase of current, the probability increases by 60% approximately when the other conditions keep unchanged.

c. The arc plasma jet flow of the bridge-type contacts is observed in the simulation, the calculated arc flow velocity field shows that the circular vortex is a reification of the arc plasma jet flow progress, the combination of volume force and contact surface roughness is the main reason of the arc jet flow.

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