MHD MODELING OF AC FAULT ARC IN A CLOSED AIR CONTAINER

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ABSTRACT

The characteristic of fault arc ignited between two metal rod electrodes in a closed air container with AC current has been investigated in magneto-hydrodynamic (MHD) method. Based on a set of governing equations in coupled electromagnetic and gas dynamic fields, a three-dimensional (3D) air arc model is constructed and solved, which predicts the distributions of temperature and pressure of arc plasma with the temperature, flow, electromagnetic, turbulence and radiation field taken into account. Particularly the internal pressure development at different locations in the container are calculated and compared. Besides, the fraction of electric arc energy leading to pressure rise, which is known as kp factor and calculated according to measured experimental results before, is determined by using the numerical method alone without any experimental data supporting. The effect of different radiation models on pressure rise is analyzed and compared. The result shows that the semi-empirical radiation model is more suitable to the pressure calculation in comparison to the net emission coefficients(NEC) model. The simulation results of the pressure rise, kp, arc voltage and arc power agree with the experiments.

1. INTRODUCTION

When a fault arc occurs in a closed electrical equipment, it releases huge energy and heats the surrounding gas, bringing about rapid pressure rise. The overpressure does not only threat the personnel safety but also damages the equipment around seriously. Hence, it is necessary to investigate the internal phenomenon and various effects of fault arc, providing theoretical basis for designing the switchgears.

In the past, some researchers had focused on the pressure rises due to fault arc, including Standard Calculation Method (SCM) and Computational Fluid Dynamics method (CFD)[1,2,3]. However, in the above both methods, the complex coupled interactions among the flow, electromagnetic fields generated from the fault arc as a electric conducting fluid are not considered. Instead, the arc is isolated and treated as a simplified heat source and the arc itself is not modelled and analyzed. In addition, the biggest disadvantage for both methods is that the pressure development can be calculated only when the fraction kp of electric arc energy leading to pressure rise, known as thermal transport coefficient[2,3], is obtained in advance according to experimental data and fitted to the simulation.

In this paper, MHD modeling is proposed to investigate the characteristics of fault arc in a closed air container theoretically. A 3-D model of air arc is constructed and solved, which predicts the distributions of temperature and pressure of arc plasma with coupled interactions among various physical fields taken into account. Particularly the internal pressure developments at different locations are calculated. Besides, the fraction kp is determined by using the numerical method alone without any experimental data supporting. The simulation results of the pressure rise, arc voltage, arc power and kp agree with the experimental data.

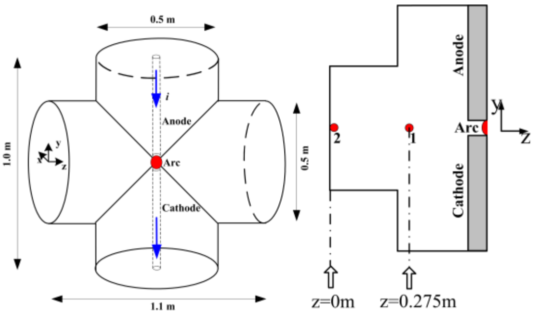
2. THE GEOMETRY MODEL

In order to reduce the complexity of the simulation, the following assumptions are adopted in this paper[4,5]:

1) The arc plasma is in local thermodynamic equilibrium(LTE) [6].

2) Vapors from the electrode and the wall are not considered.

Fig.1(a) shows the geometry of the container. The container is composed of two cylinders of 0.5m diameter with 1.0m and 1.1m in length, respectively. Two identical electrodes with 0.02m diameter are arranged symmetrically in the axis of symmetry with a gap of 30mm. An alternating current of 12.5kArms and 50Hz flows from the anode to the cathode with the arcing duration of 0.1s. The arc is ignited in the center of the container with the air filling pressure of 0.1MPa absolute. In order to save the computational cost and time, only the quarter of the geometry is taken for the symmetry of the calculated model, as shown in Fig.1(b).



（a） （b）

Fig. 1 (a) Three-dimensional geometry of the model. (b) The quarter of the simulation model in the y-z plane. (The pressure rise was measured at point 2. The pressure rises at point 1 and 2 are calculated in the model, which are denoted by dp1 and dp2.)

The characteristics of fault arc in a closed container are described numerically by the MHD governing equations, including mass, momentum, energy and Maxwell equations, respectively [7,8,9]. The plasma physical parameters of air are obtained from[10], which depend on the temperature and pressure. In addition, the turbulence is described by the standard $k-\varepsilon$ model[11] and the radiation is also taken into account with the semi-empirical model based on NEC.

3. RESULTS AND ANALYSIS

The temperature evolution of arc plasma from 0 to 20 ms is shown in Fig.2. The initial arc is a high temperature arc column. As the arc gradually expands outwards, the surrounding temperature rises continuously. At the current zero of t=10 ms, with the current dropping fast, the Joule heating decreases greatly. Afterwards, the temperature rises again. The arc goes on arcing until the next current zero. In the next period from 20 to 100 ms, the temperature sequence distributions during every current cycle are similar to that of 0-20 ms.

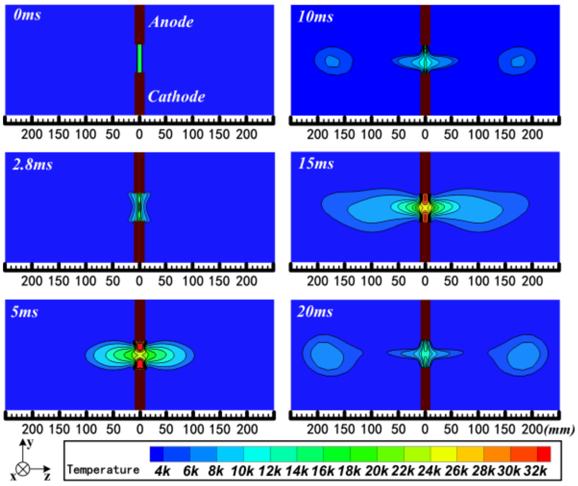


Fig.2 Temperature distribution in the arc region

Fig. 3 shows the pressure distribution within the closed container at several times. As the arcing time goes, the arc energy is injected and accumulated continuously to increase the gas internal energy, which causes pressure to build up. High pressure generated in the center rapidly propagates to the surrounding space in the form of pressure waves. When the pressure wave reaches the walls, reflections on the wall are generated, causing the pressure rising with oscillation slowly. Finally at t=100 ms, the maximum pressure rise is reached with the arc extinguishing.

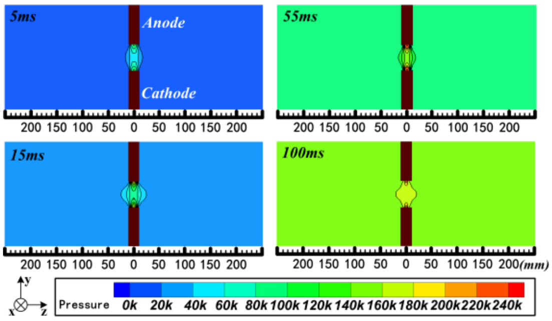


Fig. 3. Pressure distribution within the whole container

Fig.4 shows measured and calculated pressure developments with the arc current of 12.5kA and duration of 0.1s at different locations marked in Fig.1.(b). The pressure rise was measured at point 2 before[12]. The calculated pressure rise for dp1 is almost identical to that of dp2 in that the pressure waves generated in the arc core propagate around immediately at very high speed. The calculated dp1 and dp2 are both oscillation waveforms with the pressure value increasing gradually, which results from the continuous propagation of pressure waves in space and pressure-wave reflections on the walls. The oscillations of dp2 exceed those of dp1 due to more serious superposition of the pressure waves reflected on the walls at point 2. The calculated pressure rise for dp2 agrees well with that of the experiment.

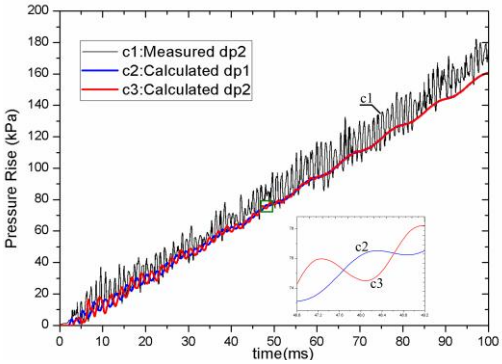


Fig.4 Calculated and experimental pressure developments at different locations in the container

The pressure developments in the container are seriously affected by the radiation of fault arc. Fig.5 shows the calculated pressure rise for dp2 with 12.5kA based on NEC and the semi-empirical model. Obviously, the dp2 using NEC method is much less than that using the semi-empirical model, which agrees well with the experimental result. It implies that with the re-absorption of the radiation in NEC model neglected, a large amount of radiated energy from the arc is lost groundlessly, leading to evident less pressure rise.

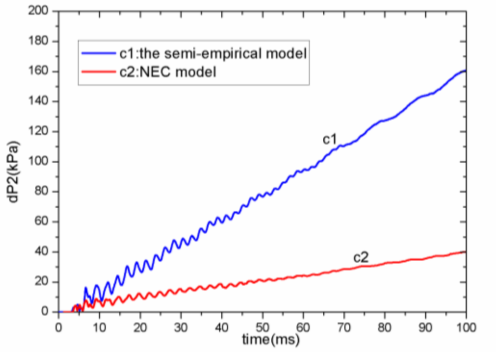


Fig. 5 Calculated pressure rise for dp2with 12.5kA based on NEC and the semi-empirical model.

The predicted pressure developments of dp2 for different arc currents are given in Fig.6. The pressure rise increases gradually with the current increasing. At 100ms, the maximum pressure rises for 4, 8 and 12.5kA all agree well with those investigated in[13].

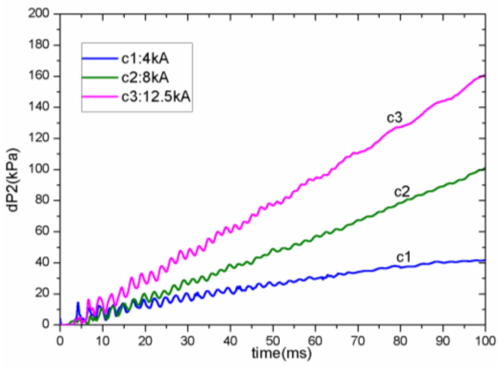


Fig. 6 The predicted pressure developments of dp2 for different arc currents(4kA, 8kA and 12.5kA/50Hz)

In the past, kp was determined only by knowing the experimental data in advance. Now here, kp can be easily predicted by the calculation alone according to the following formula[3]:

$$k_p = \frac{dP \cdot V \cdot M \cdot C_v}{R \cdot Q_{arc}} \tag{1}$$

Where C_v is the specific heat of the gas at constant volume, V the volume of the container, M the molar mass of the gas, R the molar gas constant, dP the pressure rise and Q_{arc} the electric arc energy.

Fig.7 and Fig.8 show the dependence of kp on arc current and arc energy, respectively. which is close to the experiment[12]. This means that with no complex experimental platform, kp will be easily obtained by the MHD method alone.

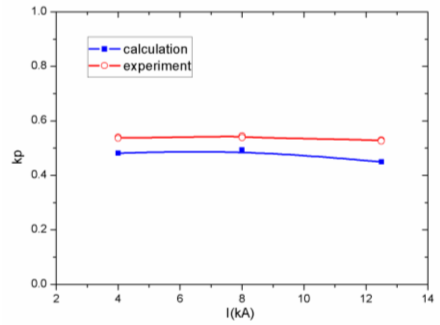


Fig. 7 Dependence of kp on arc current

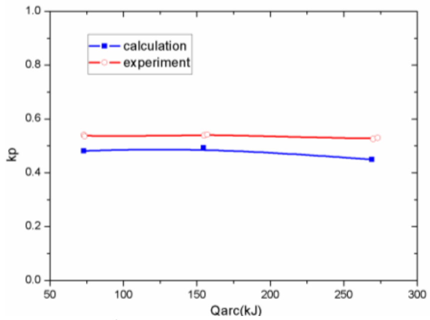


Fig. 8 Dependence of kp on arc energy

The computational arc voltage and arc power are compared with the experimental result[13], as shown in Fig.9. The computed arc voltage and arc power both agree well with corresponding experimental results with the uncertainty of 8.12% and 9.84%, respectively.

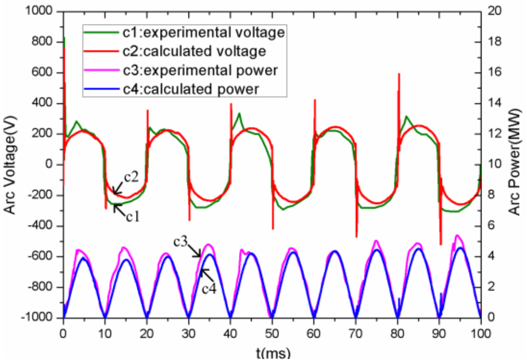


Fig. 9 Computational arc voltage and arc power in comparison to the experimental results

4. CONCLUSION

The 3-D MHD model of air arc predicts well the distributions of temperature and pressure as well as arc voltage to study the characteristics of fault arc. Particularly the internal pressure rises at different locations within the container are calculated. In addition, kp is determined by the simulation method alone without any experimental data supporting. Compared with the NEC model, the semi-empirical radiation model is more suitable to the pressure calculation in fault arc. The simulation results of the pressure developments, kp, arc voltage as well as arc power agree with the experimental data. Anyway, it can be concluded that MHD method is a reliable tool to describe the behavior of fault arc.

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