

Comparative Analysis of 2D and 3D Modeling of Transient Arc Discharges Along Guided Copper Rails

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This paper presents a comparative analysis of 2D and 3D modeling of transient arc discharges along guided copper rails, evaluating their capabilities and limitations. The 2D approach is shown to offer practical insights and efficiency, making it valuable for preliminary studies, though it exhibits certain deviations from the detailed representations achieved with 3D simulations. The study aims to highlight how far 2D simulations can approximate transient arc behavior under varying conditions. Results are benchmarked against experimental data and extended to assess the validity of 2D approximations across a range of scenarios. By exploring the trade-offs between computational cost and accuracy, this work advances the methodology for modeling transient arcs and provides guidance for selecting appropriate simulation strategies.

Index Terms— Arc discharges, magnetohydrodynamics, numerical simulation, transient analysis.

I. INTRODUCTION

ELECTRIC arcs are high-temperature, continuous electrical discharges that result from electrical breakdown, carrying currents that range from a few amperes to several kiloamperes with voltage drops typically in the tens of volts at atmospheric pressure. These arcs can reach temperatures as high as 20,000 Kelvin and are employed in numerous industrial applications, such as welding, spraying, and cutting. However, unintended arcs in systems like circuit breakers, fuses, and power transmission lines can cause significant damage and reliability issues. Understanding the dynamics of arc discharges is therefore critical for both mitigating adverse effects and optimizing their controlled use.

Experimental studies on arc discharges date back to the late 19th century [1]. Since the 1980s, numerical studies have emerged that cover both stationary arcs used in welding processes [2] and transient arcs in circuit breakers [3]. Verification and validation are necessary for numerical modeling [4]. In this study, we compare the capabilities of 2D and 3D simulations for modeling transient arc discharges along guided copper rails. While 3D simulations are considered the gold standard for capturing the full range of physical phenomena, they are computationally intensive, limiting their accessibility for iterative studies and broad parameter sweeps. On the other hand, 2D simulations provide a computationally efficient alternative, offering insights into arc behavior that are particularly useful in early-stage investigations or for establishing baseline performance.

The objective of this research is twofold: first, to evaluate the extent to which 2D simulations can approximate the behavior of transient arcs under varying conditions; and second, to delineate the limitations and trade-offs associated with 2D approaches compared to 3D modeling. Benchmarking against experimental results and exploring scenarios with diverse geometries and boundary conditions, this work seeks to establish a foundation for selecting appropriate modeling

strategies for transient arcs. Ultimately, it aims to inform future research on optimizing simulation methodologies while maintaining a balance between computational efficiency and accuracy.

II. NUMERICAL MODEL

Electric arcs are usually described with a set of partial differential equations, referred to as magnetohydrodynamics (MHD) models [5]. The simplest form is given as below:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (1)$$

$$\nabla \cdot \mathbf{J} = 0 \quad (2)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (3)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \mathbf{K} + \mathbf{F} \quad (4)$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \quad (5)$$

Equation (1) is the Ampère's law used to compute magnetic field $\mathbf{H}$ generated by the total current density $\mathbf{J}$. Equation (2) is the current conservation equation. Equation (1) and (2) are reformulated by the $\mathbf{A}$ - V formulation where $\mathbf{A}$ is the magnetic vector potential and V is the electric scalar potential. Equation (3) is the mass conservation equation. Equation (4) is the momentum conservation equation used to compute velocity field $\mathbf{u}$, where p is the pressure, $\mathbf{K}$ is viscous stress tensor and $\mathbf{F}$ is the volume force vector. Equation (5) is the energy conservation equation used to compute gas temperature T .

Equations (1-5) are fully coupled through the source contributions of current, force and energy. The total current $\mathbf{J}$ has the external induced current caused by electromotive force. The force $\mathbf{F}$ has the contributions from the Lorentz force. The energy source terms Q contains electromagnetic heating, joule heating and radiation losses. The thermodynamic properties of thermal equilibrium air are taken from [6].

The computation domain includes an air box much larger than that used for fluid flow and heat transfer simulations. The

computation domain only includes half of the geometry. At the symmetry plane, the boundary conditions are given by

$$\mathbf{n} \times \mathbf{H} = \mathbf{0} \quad (6)$$

$$\nabla \cdot \mathbf{J} = 0 \quad (7)$$

$$\mathbf{u} \cdot \mathbf{n} = 0 \quad (8)$$

$$\mathbf{n} \cdot k \nabla T = 0 \quad (9)$$

III. EXPERIMENTAL SETUP

The experiment aims to measure the current, voltage, displacement of electric arcs moving in a guided copper rail. The external circuit and experimental setup are illustrated in Fig. 1(a). The pulse forming network (PFN) is employed to generate a unipolar impulse current waveform. The capacitance of C and the inductance of L is 4.2 mF and 0.72 mH, respectively. The capacitor C is charged by a positive voltage U_C and the PFN is triggered by the thyristor TA. The diode VD₂ is inversely connected in parallel with the capacitor to avoid current oscillation. In order to ignite the electric arc between the conducting rail, a thin wire connecting the upper and lower rail is installed at a position 230 mm from the end of the rail track. The radius of the wire is 0.08 mm. The dimension of the copper rails is shown in Fig. 1(b).

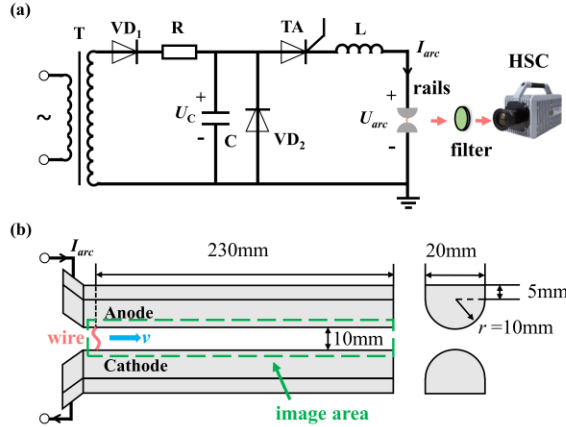


Fig. 1. Experimental setup (a) electrical circuit (b) setup.

The capacitor voltage U_C is measured by Tektronix 6105A. The voltage between the anode and cathode of rail is measured by using a high voltage differential probe (Tektronix THDPO200 200MHz), which is referred to as arc voltage in the following discussion. The arc current is measured by a Rogowski coil (PEM CWT-30LFB). All electrical signals are acquired using a Tektronix MDO3014 oscilloscope.

The Photron FASTCAM SA-X2 high-speed camera (HSC) is utilized to record the movement of triggered arc. The high-speed camera is operated at a frame rate of 50 kfps with a resolution of 768×328 pixels. A series of experiments with different charging voltages of the capacitor ($U_C = 200, 400, 600$ and 800 V) are conducted. The speed of arc root is computed based on photo images.

IV. RESULTS AND DISCUSSIONS

The initial condition for the gas temperature is given by

$$T = T_0 e^{-[(x-L_x)/r_x]^2 - (y/r_y)^2} + T_b \quad (10)$$

where $T_0 = 16$ kK, $L_x = 20$ mm, $r_x = 1.5$ mm, $r_y = 1.0$ mm, and $T_b = 293.15$ K. The numerical model is setup and run with COMSOL Multiphysics software (Version 6.3). The transient study is initialized with the result from solving equation (1) and (2) when the bridge wire melts. The transient study is solved in two segregated steps, the first for A and V using an iterative solver (GMRES); the second for T , $\mathbf{u}$ and p using a smoothed aggregation algebraic multigrid method. For the 2D model, the out-of-plane thickness is set to 6 mm.

The comparison of the measured arc voltage and arc displacement with the simulated values from 3D and 2D models are shown in fig.2 (a) and (b), respectively.

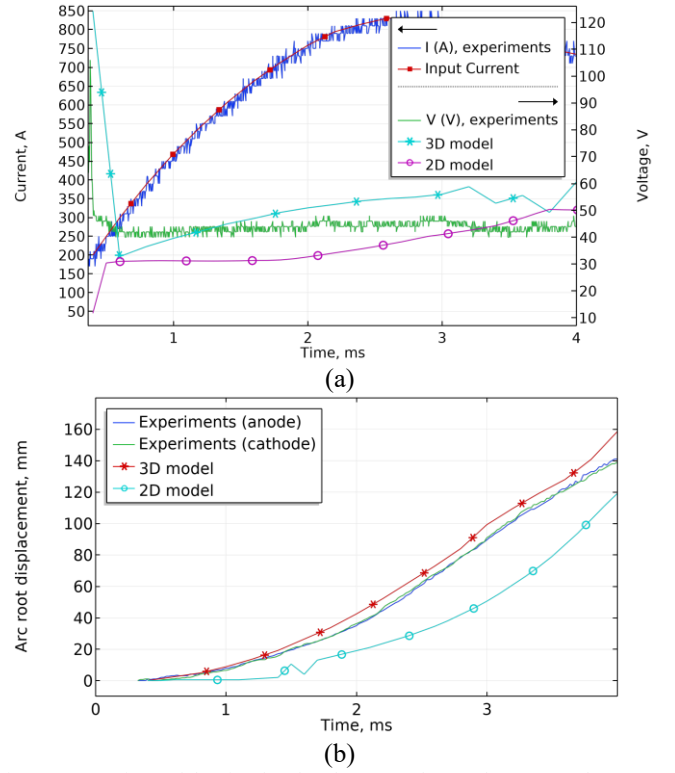


Fig. 2. Comparison of the simulated and measured arc voltage (a) and arc displacement (b).

REFERENCES

- [1] Ayrton, Hertha. *The electric arc*. Cambridge University Press, 2012.
- [2] Hsu, K. C., K. Etemadi, and E. Pfender. "Study of the free-burning high-intensity argon arc." *Journal of applied physics* 54, no. 3 (1983): 1293-1301.
- [3] Yang, Fei, Yi Wu, Mingzhe Rong, Hao Sun, Anthony B. Murphy, Zhigang Ren, and Chunping Niu. "Low-voltage circuit breaker arcs—simulation and measurements." *Journal of Physics D: Applied Physics* 46, no. 27 (2013): 273001.
- [4] Sargent, Robert G. "Verification and validation of simulation models." In *Proceedings of the 2010 winter simulation conference*, pp. 166-183. IEEE, 2010.
- [5] Comsol AB. "COMSOL multiphysics user's guide." *Version: 6.3* (2024).
- [6] Boulos, Maher I., Pierre Fauchais, and Emil Pfender. *Thermal plasmas*. Vol. 1. Springer Science & Business Media, 1994.