# A comparative study of K-epsilon turbulence model in DC circuit breaker

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## ABSTRACT

This paper focuses on the numerical investigation of arc plasma behaviour in air direct current circuit breaker (DCCB) considering the effect of turbulence with K-epsilon model. A three-dimensional simulation model of a certain type air DCCB is built and calculated, which is based on magneto-hydrodynamic (MHD) theory. Electromagnetic and gas dynamic interaction is considered through solving the Navier-Stokes equations coupled with Maxwell equations, which are connected by source terms (Joule heat and Lorentz force calculated in electromagnetic field) in the conservation equations. A thin layer of nonlinear electrical resistance model is used to represent the anode and cathode falls of arc runner produced by plasma sheath [1-2]. In the simulation results, the arc plasma shape and motion are described in detail by the temperature distributions. Some important phenomena are observed in the simulation, such as the different arc shapes, moving speeds and so on when the turbulence is considered. Finally, with the arc voltage obtained experimentally, the simulation with turbulence considered shows much agreement with the experiment result.

## 1. INTRODUCTION

Air DCCB has been widely used in DC power distribution network which develops quickly for the advantage of simple operation, high reliability, easy maintenance and plenty of available operating data. The arc behaviour is one of the most important problem of the circuit breaker. The arc plasma moving process in the quenching chamber has an important influence on the performance of the air circuit breakers including air DCCB. So many literatures have focused on the arc modelling and experimental research [3-9]. Many investigations in low voltage circuit breakers show that in small volume and low current circuit breakers the flow is laminar in the quenching chamber [10]. But disagreement appears between the simulation and experimental results when the flow is assumed to be laminar in large volume and high current air DC circuit breakers.

In this paper, a 3-D model of a certain type air DCCB has been made and applied based on the magneto-hydrodynamics theory. A thin layer of nonlinear electrical resistance model is considered to present the anode and cathode voltage fall caused by the runner plasma sheath. Simulation comparison has been done between the laminar state of the fluid and the turbulence state with the standard k-epsilon model.

## 2. THE ARC PLASMA MODEL

The model described in this paper is based on MHD theory. The behaviour of the arc is determined by the interaction of gas dynamic and electromagnetic, which is described by Navier-Stokes equations and Maxwell equations, respectively. All the equations describing the arc model can be written in a general formation as follows:

$$\frac{\partial(\rho\Phi)}{\partial t} + \nabla\cdot(\rho\Phi\mathbf{V}) = \nabla\cdot(\Gamma_\Phi\nabla\Phi) + S_\Phi \quad (1)$$

where $\Phi$ is the field variable, $\Gamma_\Phi$ is the corresponding property coefficient and $S_\Phi$ is the source term. The variables, coefficients and source terms for all the second-order partial differential equations are given in [2].

The standard k-epsilon model is a semi-empirical model based on transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The transport equation for k is derived from exact equation, while the one for ε is obtained using physical reasoning and bears some resemblance with its mathematically exact counterpart. Assuming the flow is fully turbulent and the effects of molecular viscosity are negligible, the k-epsilon equations are derived. The equations for turbulent kinetic energy and its dissipation rate are as follows:

$$\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M + S_K \quad (2)$$

$$\frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon}S_{ij}\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (3)$$

where $G_k$ represents the generation of turbulence kinetic energy due to the mean velocity gradients. This term is termed as: $G_k = \mu_t S^2$, where S is modulus of the mean rate of strain tensor, defined as $S = \sqrt{2S_{ij}S_{ij}}$ , $S_{ij}$ being the symmetric tensor equal to $\frac{1}{2}(\mu_{i,j} + \mu_{j,i})$. The term $G_b$ is the generation of turbulence due to buoyancy. $Y_M$ represents the effect of compressibility on turbulence. This phenomenon is called dilatation-dissipation. $S_K$ and $S_\varepsilon$ are user-defined source terms. The coefficient $C_{3\varepsilon}$ is not specified, but is calculated. $C_{1\varepsilon}$ , $C_{2\varepsilon}$, $C_{\mu\varepsilon}$, $\sigma_k$ and $\sigma_\varepsilon$ are constants.

## 3. GEOMETRY AND BOUNDRY CONDITONS

A simplified half part of symmetric geometry (Fig.1) is used to represent the arc chamber of the certain DCCB for the convenience of simulation. The distance between the horizontal runner and the top of the splitter plates is 350mm. the dimension of the vent1 is 20mm×10mm in the x and y direction. The dimension of vent2 is 605mm×100mm in the x and y direction. The current (I) passes through the anode, arc, cathode as shown in the Fig.1. The nonslip boundary condition is applied to the arc-wall interfaces. All the outside walls of the chamber have the same temperature $T_w$=300K. At the interfaces between the electrodes and plasma, and between the plates and the plasma, the heat is transferred to the electrodes and plates according to the energy conservation law. Thus the temperature of the elements on each side of the plasma-electrode and plasma-plates interfaces is coupled in the calculation. The self-magnetic produced ty the current passing through the electrodes and the plasma is calculated with potential vector. A current density is imposed to the anode and the potation of the cathode is assumed to be zero.

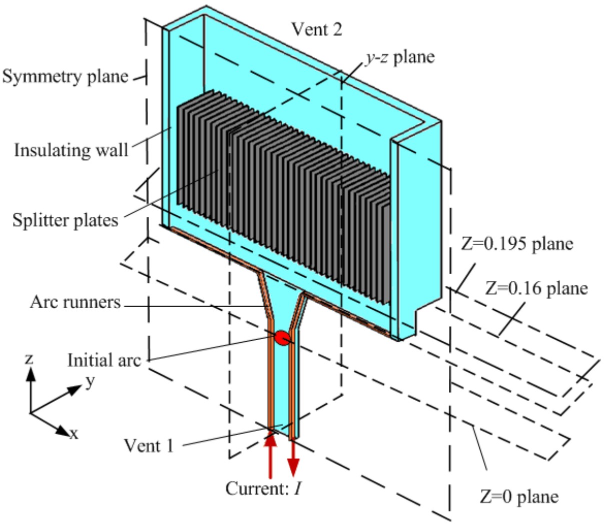


*Fig.1. schematic diagram of the arc chamber*

## 4. RESULTS AND ANALYSIS

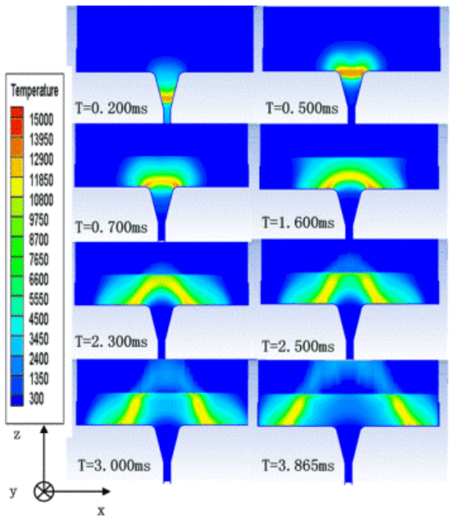


*Fig.2 temperature distribution on symmetry plane (turbulence fluid condition)*

When the fluid condition is set to turbulence, the corresponding temperature distribution sequences on the symmetry plane, the y-z plane, z=0.195m plane are shown in Fig.2, Fig.3 and Fig.4 respectively.

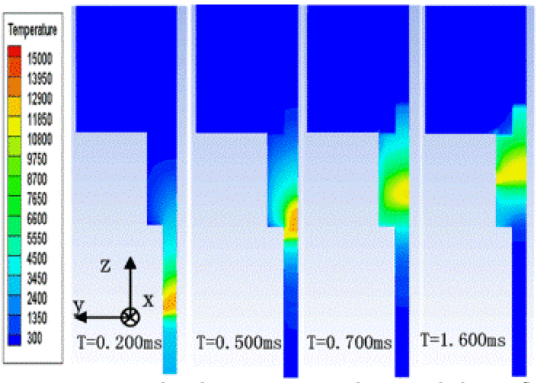


*Fig.3 temperature distribution on y-z plane (turbulence fluid condition)*

By the contrast of the calculated results with turbulence and laminar fluid condition (Fig.5), the arcing processing lasts about 3.9ms with the turbulence fluid condition while about 1.2ms in the laminar case. From the initial igniting zone to the entrance of the arc chamber along the diagonal runners, the turbulence case takes about 0.5ms and the laminar one about 0.49ms. This signifies the fluid condition exerts a little influence on this period of arcing propagation.

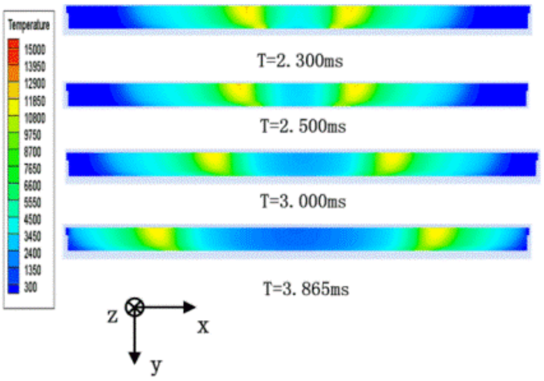


*Fig.4 temperature distribution on z=0.195 plane (turbulence fluid condition)*

After the arc crosses the runner corners and reaches the horizontal runners, the two cases show big difference. In the laminar case, the arc column stretches itself much and runs quickly towards the splitter plates. That means most time of this period the arc burns with a long arc column and high arc voltage (Fig.5). And in the turbulence case, the arc column reaches the bottom of the splitter plates until t=2.3ms, while in the laminar case it takes much less time. Then in both cases the arc columns stretch themselves into the splitters plates and are cut into several pieces. But in the laminar case the arc roots move quickly and reach the end of the horizontal runners with a time less than 1.5ms and at last it burns out (Fig.5), while in the turbulence case, the force imposed on the arc to make it run oppositely is weaker, the arc columns run slower on the way to the end of the horizontal runners. Especially, one import phenomenon is that after the column enters the entrance of the arc chamber entirely, in the turbulence case, the radius of the arc column is nearly equal to the radius of the arc column, which means that the contraction of the arc root is not obvious. And in the turbulence case, the arc root moves behind the arc column which means the hydrodynamic force imposed on the arc column is slightly weaker.

Another important difference is the arc column core temperature and its shape. In the turbulence case, the arc temperature hardly surpasses 15000K, while the laminar case arc core temperature is 20000K most of the arcing process. As in the turbulence case, the fluid particles interact with each other in all directions, thus the Joule heat produced in the arc column can be transferred efficiently. While in the laminar case, the parallel movement of the fluid particles is assumed, the energy and substance interaction is almost layer to layer, which results in the higher temperature of the arc column core.

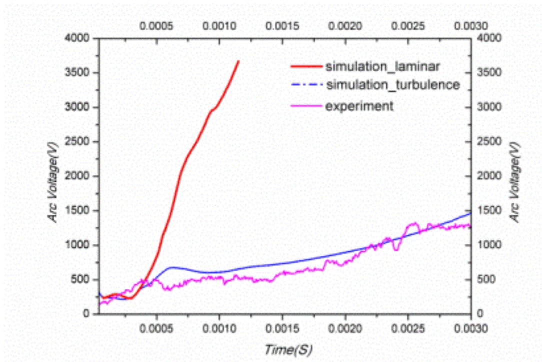


*Fig.5 comparison of the experimental and calculated arc voltages*

The difference between the arc column temperature results in the difference between the shapes of the arc column. In the turbulence case, the high temperature zone is extensive and the arc column is surrounded by a relatively larger area of high temperature. But in the laminar case, the high temperature zone is converged and at the edge of the arc column the temperature gradient is larger than that of the turbulence case. Besides, from Fig.3 and Fig.4, the profile of the arc column in the y and z directions can be seen clearly. In the y direction the arc column almost extends itself to the wall of the chamber at the beginning period which means that the turbulence develops completely even in the narrow area between the two diagonal runners.

The extension of the arc column in the z direction reflects the fore imposed on the arc column clearly. With slowly changing and relatively weaker force, the arc column in the z direction forms nearly a semi-circle, which is the case Fig.3 shows. This situation can also be identified in Fig.4. Fig.4 shows the temperature distribution on the y=0.195m plane, which describes the arc movement after the arc column crosses over the corner between the diagonal and the horizontal runners. From t=2.3ms to t=3.865ms, the arc column almost fill the chamber in the y direction, which signifies that in a space larger than the igniting area, the turbulence effect is more distinct.

Fig.5 shows the comparison of the experimental and the calculated arc voltages. It is clear that the arc voltage of the laminar case is much higher than the experimental one and laminar fluid condition can't be applied to this geometry and current case. The calculated arc voltage in the turbulence case shows a certain agreement with the experimental one in the trend and the value. As to the difference between them, the applicability of the k-epsilon model in the FLUENT and the neglect of the details such as the erosion and the sheath around the splitter plate result in this. Further worker such as adapting the k-epsilon model in the FLUENT to represent the turbulence occurring in this type of DC circuit breaker should be taken on.

## 5. CONCLUSION

A comparative study of the arc motion is investigated through simulation in the turbulence (k- epsilon model) and laminar case in this paper. The difference of the arc column motion from the igniting to the burning out is emphasized. The conclusion is that: 1) the arc in the laminar case moves faster than in the turbulence case, 2) the temperature of the arc core in the laminar case is much higher than in the turbulence case, 3) the arc voltage in the turbulence case shows agreement with the experimental one, which not happens to the laminar case. In this kind of geometry and current, turbulence fluid condition is more suitable than laminar.

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