Study of the Flow on No-Load Breaking of SF₆ Circuit Breaker Based on Lattice Boltzmann Method

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Abstract. In the simulating breaking of SF₆ circuit breaker with the finite difference method and finite element method, there are some disadvantages such as a long calculation time and a complex calculation procedure. In this paper, a new method which is based on the lattice Boltzmann method (LBM) is presented to simulate the breaking process in an SF₆ circuit breaker. And the model of nozzle arc is established by the lattice Boltzmann method. The flow in the arc-extinguishing chamber is calculated with the LBM. The pressure and velocity fields of the upstream and throat of the nozzle in the chamber are obtained by the simulation. Compared with the test data, they are good agreement. The results show the feasibility and correctness of the lattice Boltzmann method in studying the evolution of gas flow of nozzle during the breaking.

1. Introduction
High voltage circuit breaker is the key equipment to control and protect the safe operation of power grid. It has been widely used in high voltage and ultra-high voltage systems. To some extent, it reflects the development level of a country's power industry [1]. Based on the study of the arc models and arc dynamic characteristics, the numerical calculation and analysis methods are used to study various physical phenomena in the arc-quenching chamber. The breaking performance of circuit breaker is deeply analysed, so as to improve the design level and shorten the design cycle, and create conditions for the performance of new products. However, the breaking characteristic of circuit breaker is a very complicated physical and chemical process, which involves the change of arc and its physical properties. At present, some breaking phenomenon has not been thoroughly studied [2]. So the research of arc theory and numerical calculation of circuit breaker are still a very meaningful work.

The studies on circuit breaker arc models and breaking characteristics have been carried out for many years, from the early CASSIE and MAYR [3] arc models, the one-dimensional arc dynamic models in the 1970s, the two-dimensional arc models in the 1980s, to the study on the two-dimensional nozzle arc plasma models in the 1990s [4-7]. They are all the macroscopic models of the circuit breaker. In recent years, many scholars have also studied the non-equilibrium effect of SF₆ arc plasma from the microscopic models. Based on the theory of the local thermodynamic equilibrium assumption and magnetohydrodynamic (MHD), a complete mathematical model of SF₆ plasma arc is established. Considering the dynamic effect of arc energy on the electron temperature and heavy particle temperature in the plasma, a mathematical model of unbalanced double temperature arc is established [8]. Currently,
the SF₆ arc models are mainly based on the assumptions of MHD equations and local thermodynamic equilibrium (LTE). Navier-Stokes (NS) equations are generally solved by finite difference method, fluid mesh method, finite element method and finite volume method, and etc. Since the convection item of NS equations is nonlinear, and the pressure term is implicit, the Laplace equations must be solved for each step of calculation to meet the requirements of the continuity equations, which will spend a lot of computing time. In addition, general commercial fluid dynamics software cannot meet the requirements of calculation. So secondary development is required to solve the applications.

The lattice Boltzmann method (LBM) is a mesoscopic model between the microscopic molecular dynamics model and the macroscopic continuous model. The method is based on kinetic theory. Because of its kinetic nature and relatively easy calculation procedure, the LBM has a very wide applications in multiphase multicomponent flow, plasma jet, suspended particle flow, argon arc plasma welding, engineering heat transfer, turbulent flow calculation, and magnetohydrodynamic, and etc. [9-12]. In recent years, LBM has become a new idea for the study of fluid. In this paper, LBM is used to study the evolution of flow field during the no-load breaking process of SF₆ circuit breaker, which is a brand-new nozzle arc model and simulation work. At present, relevant research results at home and abroad have not yet been seen. In LBM, the convective term is a linear migration process, and the pressure can be directly solved according to the density. There is no need to use fluid software. The collision and migration processes are local and can be easily processed in parallel on the computer.

2. Mathematical modeling

2.1. The kinetic equation for flow field of nozzle arc

The velocity distribution function is able to be derived from the Boltzmann equation. So the Boltzmann equation of the arc plasma is expressed as [13]:

$$\frac{\partial f}{\partial t} + v \cdot \nabla f^* + a \cdot \nabla_f f^* = \left( \frac{\delta f}{\delta t} \right)_\text{coll}$$  \hspace{1cm} (1)

Where \(f\) is the distribution function of particle in phase space \((x, v)\) at time \(t\); \(x=(x, y, z)\) is the position vector; \(v\) is the microscopic velocity vector; \(a\) is the acceleration of the particle in the magnetic field by the Lorentz force.

Due to the no-load breaking of the SF₆ circuit breaker, no arc is generated. So particles are not affected by Lorentz. Boltzmann-gross-krook model assumes that collisions between molecules will cause the distribution function \(f\) to approach its equilibrium state, and the variables caused by collisions are proportional to the extent that function \(f\) deviates from the equilibrium state. The Bhatnagar-Gross-Krook (BGK) [14] equation is expressed as:

$$\frac{\partial f}{\partial t} + v \cdot \nabla f^* = -\frac{1}{\tau_f} (f^* - f^{eq})$$  \hspace{1cm} (2)

Where \(\tau_f\) is the relaxation time, \(f^{eq}\) is the equilibrium distribution function.

2.2. The Lattice Boltzmann equation

The Lattice Boltzmann equation is a special discrete form of Boltzmann-BGK equation, including velocity discrete, time discrete and space discrete. The nozzle arc is a two-dimensional axisymmetric model. Since the D2Q4 and D2Q5 models cannot guarantee the macroscopic isotropic and the independence of velocity to pressure in NS equations, the D2Q9 model is adopted in this paper. Eq. (2) is expressed as the evolution equations in Eq. (3) in the lattice system [13]:
\[ f_{k}^{eq}(x + e_k \delta t, t + \delta t) = f_{k}^{eq}(x, t) - \frac{1}{\tau} \left[ f_{k}^{eq}(x, t) - f_{k}^{eq}(x, t) \right] \]

Where symbol \( k \) denotes the diffusion direction; \( f_{eq} \) is the equilibrium distribution function in the lattice unit system; \( e_{k} = \frac{\delta x}{\delta t} \) is the diffusion velocity within the lattice system \( \delta x, \delta t \) denote the grid step and the time step, respectively; \( \tau = \nu \frac{\delta x^2}{c_s^2} + 0.5 \) is the lattice relaxation time; \( \nu \) is the kinetic viscosity.

Figure 1. D2Q9 lattice model particle distribution

The diffusion velocity, equilibrium distribution function, and weight coefficient of D2Q9 lattice model are expressed as in Eqs. (4), (5) and (6), respectively:

\[ e_k = \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \end{bmatrix} \]

\[ f_{k}^{eq} = \omega_k \rho \left[ 1 + \frac{(e_k \cdot u)^2}{c_s^2} + \frac{(e_k \cdot u)^2}{2c_s^4} - \frac{u^2}{2c_s^2} \right] \]

Where \( c_s = c/\sqrt{3} \) is the lattice sound speed of species; \( c = \frac{\delta x}{\delta t} \) is the lattice unit speed; \( w_k \) is the lattice weight coefficient. \( w_k \) is 4/9 for \( \alpha = 0 \), 1/9 for \( \alpha = 1, 2, 3, 4 \), and 1/36 for \( \alpha = 5, 6, 7, 8 \). \( u \) is the macroscopic speed; \( \rho \) is the density. The evolution process of the LBGK model can be divided into two sub-processes: collision and migration:

1. Collision process

\[ f_{out}^{eq}(x, t) = f_{in}^{eq}(x, t) - \frac{1}{\tau} \left[ f_{in}^{eq}(x, t) - f_{eq}^{eq}(x, t) \right] \]

2. Migration process

\[ f_{in}^{eq}(x + e_k \delta t, t + \delta t) = f_{out}^{eq}(x, t) \]

Where \( f_{in} \) is the velocity distribution function of particles flowing into the grid points; \( f_{out} \) is the velocity distribution function of particles flowing out of the grid points.

By using the relationship between the macroscopic parameters and the distribution function, the macroscopic parameters related to the fluid flow in plasma can be obtained by:
\[ \rho = \sum_k f_k \rho \quad \rho u = \sum_k e_k f_k \]
\[ \rho uu + \rho I = \sum_k e_k e_k f_k \]

(8)

Where \( p = c_s^2 \rho \) is the pressure of the particle; \( I \) is the unit matrix.

2.3. The unit conversion
Clarification of the relationship between the physical unit system and the lattice unit system is necessary in order to solve real physical problems using the LBM and to maintain stability of the model. The majority of the physical units can be expressed by the combination of the main several units, i.e., length, time, density, and speed. In lattice unit system and the physical unit system, the length, density, and speed of sound are expressed as \( L' \), \( \rho' \), \( c_s' \). Therefore, the rescaling coefficients of \( L = L' / L, \rho = \rho' / \rho, c_s = c_s' / c_s \) are given \([10]\). In lattice system, \( L, \rho, c_s \) is known, the physical unit of \( L', \rho', c_s' \) are given by the formula. The macro Reynolds number is equal to the lattice Reynolds number, which is expressed as

\[ \text{Re} = \frac{uL}{\nu} = \frac{u'L'}{\nu'} \]

(9)

And the rescaling coefficients for kinetic viscosity and pressure are expressed as \( \nu_r = L_r u_r \), \( p_r = u_r^2 \rho_r \), respectively.

3. Results and discussion
In this paper, the 252kV circuit breaker is taken as the research object, and the circuit breaker structure is simplified to obtain the calculation area of the nozzle arc as shown below.

As shown in the figure 2, OD is the inlet of airflow, BC is the outlet of airflow, and AB is the axis of symmetry. The test points of the upstream, throat and downstream of the nozzle are shown in the Figure 2. The actual physical size of the nozzle is 220mm×36mm. In the lattice system, the calculation area is divided into 220×36, and each small grid is 1mm. The initial conditions of the nozzle are as follows that the base pressure is 0.7MPa, the initial temperature is 300k, and the initial velocity is zero. Macro boundary conditions are given as a function of pressure changing with time at the inlet to simulate the pressure changing of the compressor chamber, as shown in figure 3 (the pressure in the figure 3 is incremental). The pressure of the outlet of airflow is equal to the initial pressure. For the constrictor, the velocity is zero, and the radial velocity on the axisymmetric boundary is also zero. The microscopic boundary conditions are as follows that pressure boundary conditions are adopted for inlet and outlet of the flow field, and rebound format is adopted for the constrictor boundary. Specific methods can be referred to references \([15, 16]\).
In figure 3, 1, 2 denote pressure and contact movement stroke, respectively.

In this paper, the LBM is used to analyze the calculation results of the no-load breaking of SF6 circuit breaker. According to the change of the position of the moving and static contacts, the changes of airflow characteristics can be divided into the typical three times. They are that the moving and static contacts are just separated, the main nozzle is just opened, and the main nozzle is fully opened. As shown in the figure 4, the length of the arrow indicates the velocity, and the direction of the arrow indicates the direction of the airflow.

Figure 3. Inlet pressure and contact movement stroke

Figure 4. The velocity vector and pressure diagrams at different times
As can be seen from figure 4 (a) and (b). When the moving and static contacts are just separated, the pressure is relatively high in the straight section of the inlet, and the velocity does not change substantially. The cross section area of the airflow between the contacts of the moving and static suddenly Narrows, and the airflow is accelerated here. The airflow here basically flows along the head of the static contact, and the airflow plays the role of transverse arc blowing. When entering the auxiliary nozzle, the pressure is reduced, and the velocity is still relatively large. Finally the airflow flows out through the auxiliary nozzle.

As can be seen from figure 4 (c) and (d). When the main nozzle is just opened, the airflow in the upstream region meets the airflow from the opposite direction of the symmetrical axis, and the velocity decreases gradually. At the symmetry axis position, a stagnation point with high pressure and the low velocity is formed. At the same time, due to the increase of pressure and density in stagnation zone, the pressure difference inside and outside the auxiliary nozzle is increased, and the airflow in the auxiliary nozzle is fully developed. In addition, since the main nozzle is opened, the high airflow accumulated between the moving and static contacts is released in the throat of the nozzle. The airflow not only acts as a role of transverse blowing arc, but also produces a longitudinal blowing effect.

As can be seen from figure 4 (e) and (f), when the main nozzle is fully opened, the airflow has been fully developed in the nozzle expansion zone. Due to the obstruction of the static arc contact, the velocity of the airflow in front of static arc contact decreases, and the airflow moves upward along the head of the static arc contact. At the same time, the blocking effect of the throat disappears, and the pressure on the upstream of the nozzle suddenly decreases. Therefore, when the nozzle is fully opened, the airflow plays a longitudinal arc blowing effect.

Figure 5 and figure 6 are respectively the curves of the pressure characteristics of the upstream and the throat of the nozzle with the moving time of the static contact, and the pressure in the figures is all pressurized.

![Figure 5. Contrast chart of upstream pressure](image1)

![Figure 6. Contrast chart of throat pressure](image2)

In order to validate our model, we compare the LBM simulation with the test of 252kV circuit breaker. Since the upstream of the nozzle is connected to the pressure chamber, the upstream pressure of the nozzle in figure 5 is similar to that in figure 3, and slightly lower than that of the pressure chamber. In the first 10ms, the static contact blocks the nozzle, and the upstream pressure rises slowly. The main nozzle is fully opened about 10-26ms. With the increase of pressure in the pressure chamber, the simulation and test pressures at the upstream of the nozzle are maximized at 26ms. In the later stage when the nozzle is fully opened, the pressure on the upstream of the nozzle decreases rapidly due to the disappearance of the blocking effect of the static contact, and then returns to the fundamental pressure state around 40ms. In the following ten milliseconds, the airflow oscillates around the fundamental pressure. In figure 5, we find that the LBM simulation results are basically consistent with the upstream test results of the nozzle.
In figure 6, the pressure of the throat is blocked by the static contact before 14ms, so the pressure still maintains the base pressure. Then, when the main nozzle is opened, the pressure suddenly rises. At 18ms, the pressure of the simulation and test suddenly increases to the maximum. Finally, when the throat is opened, the pressure suddenly drops. During the period of 20-38ms, the pressure of LBM simulation has a slower drop and more large fluctuation than that of the test, resulting in large errors. At present, LBM is preliminarily applied in the study of circuit breakers. Complex curved boundary problems are prone to cause unstable solutions. Therefore, when dealing with the complex boundary of the nozzle, we simplify the boundary, which leads to a large error. In addition, the rebound scheme of the solid wall boundary has only one order accuracy, and the airflow in the throat changes dramatically after the main nozzle is opened, so there is a large error in the throat. However, the overall trend of the throat pressure is consistent with the test results. The comparison of the maximum pressure between LBM simulation results and test results is shown in table 1:

| Test points                  | Maximum pressure (MPa) | Maximum pressure stroke (mm) |
|-----------------------------|------------------------|------------------------------|
| Test of the upstream        | 1.742                  | 85%                          |
| Test of the throat          | 0.975                  | 54%                          |
| LBM simulation of the upstream | 1.735               | 85%                          |
| LBM simulation of the throat | 0.954                  | 54%                          |

It can be find in table 1 that at the maximum pressure of the upstream, the pressure of LBM simulation is 0.007 MPa less than that of the test, with an error of 0.4%, and the stroke is the same. At the maximum pressure of nozzle throat, the pressure of LBM simulation is 0.021mpa smaller than that of the test, with an error of 2.2% and the same stroke difference. We verified the correctness of the LBM application in the study of the no-load airflow field of the SF6 circuit breaker.

4. Conclusion

In this paper, LBM is used to study the variation of airflow field during the no-load breaking of the SF6 circuit breaker from the mesoscopic level. Taking 252kV circuit breaker as the research object, we set the pressure with changing of time at the air inlet. Through the lattice Boltzmann method, we get the change of the pressure and the velocity in the upstream and the throat of the nozzle with the movement time of the contacts. We make a comparison between LBM simulation results and test results. The simulation pressure of the upstream nozzle is in good agreement with the test pressure. The throat pressure error is relatively large. The reason is that the complex boundary of the solid wall is simplified when dealing with the expansion zone of the nozzle, and the throat is where the airflow changes most violently. The results show that LBM is feasible and correct in studying the variation of no-load flow field in arc-quenching chamber.

Compared with the traditional finite element method and finite volume method, LBM has great advantages in computing programming and dealing with complex boundary problems in the calculation of the breaking process of the SF6 circuit breaker. However, the current LBM method is still in the initial exploration stage in the research and application of SF6 circuit breaker, so there are some errors.

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