

Article

Research on Multiphysics Coordinated Control Characteristics of 550 kV Fast Circuit Breaker Operating Mechanism and Arc-Extinguishing Chamber

Shaoan Wang ¹, Tianbo Zhang ¹, Jianwei Wei ², Qingchao Sun ², Bowen Xu ^{3,*}, Lumin Zhao ¹, Qijie Zhu ¹, Jianlei Zhao ² and Xiangwei Li ⁴

¹ State Grid Zhejiang Electric Power Co., Ltd., Electric Power Research Institute, Hangzhou 310014, China; midutisn@foxmail.com (S.W.); tbzhang113@163.com (T.Z.); lumin_zhao@126.com (L.Z.); zhuqijiecr@163.com (Q.Z.)

² Henan Pinggao Electric Co., Ltd., Pingdingshan 467001, China; weijw1030@163.com (J.W.); sunqingchao11@163.com (Q.S.); 15093807262@163.com (J.Z.)

³ Department of Civil Engineering, Design School, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China

⁴ School of Electrical Engineering, Shenyang University of Technology, Shenyang 110870, China; lixiangwei0617@163.com

* Correspondence: bowen.xu@xjtlu.edu.cn

Abstract

With the expansion of the power grid and the high proportion of new energy access, the short-circuit current level of the system is increasingly approaching the breaking limit of the circuit breaker. This paper focuses on the 550 kV fast circuit breaker, using a coupled numerical model of the operating mechanism and arc-extinguishing chamber to investigate the coordinated influence of nozzle turbulence grooves and compression cylinder diameter. It is found that the turbulence groove enhances the exchange of cold and hot airflow by inducing the recirculation zone. The turbulence groove modifies the local nozzle flow field and enhances cold-hot gas mixing, as indicated by the reduced arc-core temperature and gentler radial temperature gradient without affecting the contact motion characteristics. The maximum temperature of the arc core is reduced from 32.5 kK to 31.4 kK, and the pressure attenuation during the critical period of arc extinguishing is effectively delayed. In addition, the diameter of the compression cylinder and the opening characteristics show significant nonlinear coupling characteristics: when the diameter is 70 mm, the arc blowing strength is insufficient, and when the diameter is 90 mm, the pressure gas reaction overload inhibits the opening speed. The comprehensive analysis shows that when the diameter is 80 mm, the pressure accumulation and mechanical characteristics achieve the best balance, and the arc-core temperature is reduced to a minimum of 29 kK. Among the three investigated cylinder diameters, $D_c = 80$ mm provides the best balance between pressure build-up and operating-mechanism response when combined with the nozzle turbulence groove. This configuration provides more favorable flow-field conditions for long-arcing energy dissipation among the investigated cases. It should be emphasized that this conclusion is limited to the investigated range of $D_c = 70$ – 90 mm and should not be regarded as a global optimum.

Keywords: ballistic breaker; operating mechanism; coordinated regulation; turbulence groove; compression cylinder

Academic Editor: Krzysztof Górecki

Received: 15 June 2026

Revised: 7 July 2026

Accepted: 9 July 2026

Published: 11 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

With the continuous improvement of the scale and voltage level of China's power system, as well as the large-scale construction of new energy bases and the rapid expansion of load-intensive areas. In the process of global energy transformation, the short-circuit current problem of the power grid is becoming more and more prominent, which may produce short-circuit current, exceeding the breaking capacity of the circuit breaker. The problem of short-circuit current exceeding the standard will pose a serious challenge to the safe and stable operation of power equipment and power systems [1,2]. In order to effectively prevent the potential hazards caused by excessive short-circuit current and ensure the safe and stable operation of the power system, it is urgent to take effective measures to limit the short-circuit current to a safe and controllable range.

Given the limitations of traditional short-circuit current limiting measures, scholars have proposed flexible short-circuit current suppression technology [3]. This technology controls the fault current through accurate and fast topology reconstruction. Compared with conventional measures, it can minimize the impact on the normal operation mode of the system and achieve 'zero perception' of control impact. It is an effective new way to solve the problem of short-circuit current exceeding the standard. A fast circuit breaker is the core equipment of the new short-circuit current flexible suppression technology. The AC high-voltage fast switching scheme is mostly composed of vacuum interrupter breaking units in series and parallel. There are many breaking units, complex product structure, high costs and reliability that need to be verified [4]. High-voltage SF₆ fast circuit breakers represent a new research direction. Compared to vacuum fast circuit breakers, they not only have a simpler structure and higher reliability, but also possess strong flow and heat dissipation capabilities, are smaller in size, and are economical due to the use of SF₆ insulation material. It can be used in new power stations and old stations. However, in the research and development of 550 kV voltage level fast circuit breakers, it is still in the stage of technical exploration and prototype development. Therefore, the development of 550 kV SF₆ fast circuit breakers is necessary to solve practical engineering problems.

When the high-voltage circuit breaker interrupts the short-circuit current, the gas between the arc contacts will be heated and ionized, forming a high-temperature arc with a temperature of up to tens of thousands of kelvins and a pressure of up to several megapascals. Under the cooling effect of the upstream airflow of the nozzle and the ablation of the electrode and the nozzle material, the arc forms a complex multiphysics coupling problem involving airflow, temperature and electromagnetic field in the arc-extinguishing chamber [5]. The emergence of the two-dimensional physical-mathematical arc model in the late 1980s is a major breakthrough in the field of arc model research. [6]. Lowke et al. constructed a two-dimensional arc model in 1982 to study the changes in temperature field and velocity field in the arc-extinguishing chamber and obtained the dynamic change process of the arc [7]. In the same period, Ragaller et al. used streamer theory to study the post-zero dielectric recovery characteristics of steady-state axial gas-blown arcs [8]. Since then, the two-dimensional magnetohydrodynamic (MHD) model has become the mainstream method for domestic and foreign researchers to analyze the arcing characteristics. Yan et al. established the MHD model and obtained the evolution law of the multiphysics in the arc-extinguishing chamber during the breaking process, which provided the necessary theoretical support and technical guidance for the rapid development of high-voltage switches [9]. Pei Y et al. calculated the breaking process of a self-powered SF₆ circuit breaker by MHD model, studied the dynamic change process of arcs under different arcing time, and compared and analyzed the influence of small nozzle structure parameters on the breaking performance of self-powered circuit breakers [10].

In recent years, Rong Mingzhe, Li Xingwen, and their team at Xi'an Jiaotong University have conducted extensive research on the calculation of airflow field in the arc-

extinguishing chamber of circuit breakers. The influence of breaking current, arcing time and frequency on the arc characteristics of the circuit breaker is analyzed, and the development process and internal mechanism of the non-equilibrium arc are studied [11,12]. Jin Lijun et al. established different nozzle arc models according to the numerical analysis method and studied the influence of nozzle structure on the arc extinguishing characteristics [13]. Professor Lin Shen of Shenyang University of Technology and his team have done a lot of research on the gas flow field and breaking performance of SF₆ circuit breaker interrupters, and obtained the distribution of pressure, density, temperature, thermodynamic parameters and transport parameters in the circuit breaker interrupter, which guided the development of many circuit breakers [14,15].

At present, the research of circuit breakers has gradually shifted to the multiphysics coupling simulation stage of the whole machine. Relevant researchers have initially explored the interaction between the operating mechanism, the arc-extinguishing chamber and the arc. Ma Zeng rui et al. used Adams and MATLAB co-simulation to establish a dynamic model of a high-voltage SF₆ circuit breaker with a spring mechanism, and analyzed the dynamic change law of the gas pressure in the compressor chamber and the resistance of the buffer during the no-load opening process [16]. Guo Xing yu et al. constructed a multi-field coupling model including electric field, magnetic field, temperature field and stress field for the electromagnetic repulsion mechanism in the DC circuit breaker, compared the difference between sequential coupling and direct coupling, and analyzed the influence of key design parameters on the motion characteristics of the mechanism [17]. Zhang et al. used AMESim and Adams to combine the hydraulic buffer structure and the operating mechanism, analyzed the dynamic buffer oil pressure and fluid characteristics of the buffer structure, optimized and improved the multi-stage step buffer structure, and improved the reliability and applicability of the hydraulic spring operating mechanism [18]. Wei Jun mei et al. established a gas–solid coupling model for the arc-extinguishing chamber and the operating mechanism, and studied the flow field characteristics of the arc-extinguishing chamber of the circuit breaker and the dynamic characteristics of the operating mechanism [19].

Although previous studies have provided important insights into MHD arc modeling, nozzle flow-field analysis, and operating-mechanism dynamics of high-voltage circuit breakers, most of them focused on either the arc-extinguishing chamber or the operating mechanism separately. The coordinated influence of nozzle-induced turbulence and compression-cylinder sizing on the coupled response of contact motion, pneumatic reaction force, pressure build-up, nozzle airflow, and arc-core temperature in a 550 kV fast circuit breaker has not been sufficiently clarified. Therefore, this study focuses on the structural matching problem between the operating mechanism and the arc-extinguishing chamber of a 550 kV fast circuit breaker. Based on an established multiphysics numerical framework, two key design factors are investigated: the presence of a nozzle turbulence groove and the compression-cylinder diameter. The turbulence-groove design is evaluated under a 17 ms long-arcing condition to clarify its influence on local flow redistribution, cold–hot gas mixing, pressure retention, and arc cooling. In addition, three cylinder diameters, $D_c = 70$ mm, 80 mm, and 90 mm, are compared to reveal the coupling relationship between gas storage capacity, pneumatic reaction force, contact motion, and pressure build-up. The main contribution of this work is not the proposal of a fundamentally new MHD/CFD formulation, but the clarification of the coordinated structural-matching mechanism in a 550 kV fast circuit breaker. The results provide a comparative basis for understanding how the nozzle turbulence groove and compression-cylinder diameter affect the coupled mechanical, flow-field, and thermal characteristics during long-arcing interruption.

2. Joint Simulation Mathematical Model of Arc-Extinguishing Chamber

2.1. Current Arc Mathematical Model

2.1.1. Governing Equation

Assuming that the arc is in a local thermodynamic equilibrium state, its behavior can be mathematically described by the time-averaged Navier–Stokes equation. The LTE assumption and the two-dimensional axisymmetric formulation are adopted to reduce computational cost and to ensure consistent comparison among different structural configurations. LTE is mainly applicable to the high-temperature arc-core region during the high-current stage, while local non-equilibrium effects may occur near current zero. The axisymmetric model can describe the main arc column and nozzle flow under approximately symmetric conditions, but it cannot fully capture possible three-dimensional arc distortion or asymmetric flow separation. Therefore, the present model is mainly used for comparative analysis of pressure, airflow, and temperature evolution, rather than for direct prediction of dielectric recovery or breaking success. Under the two-dimensional axisymmetric structure, the basic governing equations are as follows [20–24]:

Mass conservation equation:

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

where ρ is the gas density; $\vec{V}$ is the velocity vector.

Momentum conservation equation:

$$\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho \vec{V} w) - \nabla \cdot ((\mu_l + \mu_t) \nabla w) = -\frac{\partial p}{\partial z} + \nabla \cdot (\bar{\tau}) + J_r B_\theta \quad (2)$$

where p is the gas pressure; w and V_r represent the axial and radial velocity of the airflow, respectively; μ_l and μ_t represent the laminar and turbulent viscosity coefficients, respectively; $\nabla \cdot (\bar{\tau})$ represents the viscous dissipation term; J_r and J_z represent the radial and axial current densities, respectively; and B_θ denotes the magnetic induction intensity.

Energy conservation equation:

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \vec{V} h) - \nabla \cdot \left(\left(\frac{k_l + k_t}{C_p} \right) \nabla h \right) = \sigma E^2 - q + \nabla \cdot (\bar{\tau} \cdot \vec{V}) \quad (3)$$

In the formula, h represents the specific enthalpy of arc plasma; k_l denotes the laminar thermal conductivity; k_t denotes turbulent thermal conductivity; C_p denotes constant pressure-specific heat; q is the radiation source term; E denotes the electric field intensity; and σ indicates electrical conductivity.

2.1.2. Turbulent Flow Model

To account for the turbulent gas flow around the arc and in the nozzle region, a standard two-equation turbulence model is adopted. This type of turbulence treatment has been widely used in engineering simulations of gas-blast interrupters [25–27]; therefore, its full derivation is not repeated here. The turbulent kinetic energy and turbulent dissipation rate are solved together with the arc-flow governing equations [28]:

Turbulent kinetic energy equation:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + P_k - \rho \varepsilon \quad (4)$$

Turbulent dissipation equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + C_1 \frac{\varepsilon}{k} P_k - C_2 \rho \frac{\varepsilon^2}{k} \quad (5)$$

$$\mu_t = C_\mu \frac{\rho k^2}{\varepsilon} \quad (6)$$

where μ denotes the molecular viscosity; σ_k denotes the turbulent kinetic energy diffusion coefficient; P_k is the turbulent kinetic energy generation term; ε is the turbulent kinetic energy dissipation rate; σ_ε is the turbulent dissipation diffusion coefficient; and C_1 , C_2 and C_μ are empirical constants.

2.1.3. Arc Radiation Model

This paper employs a six-band P-1 radiation model to account for radiative heat transfer. Compared to the net emissivity method, the P-1 model can account for radiative absorption by the surrounding low-temperature gas region, which is crucial for predicting the temperature distribution at the arc edge. The equations used in this calculation are as follows:

Radiation heat transfer has an important influence on the arc-temperature distribution in the arc-extinguishing chamber. In this study, a six-band P-1 radiation model is adopted to describe the radiation loss and radiation absorption of the arc plasma. Compared with the net emission coefficient method, the P-1 radiation model can account for radiation absorption in the surrounding low-temperature gas region, which is important for describing the arc-edge temperature and the thermal interaction between the arc core and the surrounding gas.

According to the spectral absorption characteristics of the plasma, the wavelength range is divided into six bands. The total wavelength range is $300.0\text{--}45,000.0 \times 10^{-10} \text{ m}$, corresponding to $3.0 \times 10^{-8}\text{--}4.5 \times 10^{-6} \text{ m}$, or $30\text{--}4500 \text{ nm}$. The band division and the corresponding average absorption-coefficient curves are listed in Table 1.

Table 1. Spectral bands used in the six-band P-1 radiation model.

Band i	Wavelength Range/ 10^{-10} m
1	300.0–852.2
2	852.20–1019.1
3	1019.1–1129.9
4	1129.9–1798.4
5	1798.40–11,991.6
6	11,991.6–45,000.0

$$q_r = -\frac{1}{3(a + \sigma_g) - C\sigma_g} \nabla G \quad (7)$$

where q_r represents the radiative heat flux; σ_g represents the scattering coefficient; a represents the absorption coefficient; G represents the incident radiation intensity; and C denotes the coefficients of linear anisotropic phase functions. The Γ parameter is introduced into:

$$\Gamma = \frac{1}{3(a + \sigma_g) - C\sigma_g} \quad (8)$$

In this paper, the incident radiation is solved by a custom scalar transport equation. The transport equations of G_i ($i = 1, 2, \dots, 5$) corresponding to each band of the P-1 model are as follows:

$$\nabla \cdot (\Gamma_i G_i) + S_i^G = 0 \quad (9)$$

$$\Gamma_i = \frac{1}{3a_i} \quad (10)$$

$$S_i^G = 4a_i\alpha T^4 - a_i G \quad (11)$$

where α denotes the Stephen-Boltzmann constant, $5.67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$; S_i denotes the loss of radiation energy in the medium; and a_i is the absorption coefficient corresponding to each band.

2.2. Dynamic Model of Operating Mechanism

From the above analysis, it can be seen that in the realization of the dynamic model, the basic dynamic equation of the hydraulic operating mechanism is [29]:

$$M_1 \frac{d^2x}{dt^2} = P_0 A_0 - P_1 A_1 - \kappa F_q - \beta \cdot v_h - f \quad (12)$$

The dynamic model of the mechanism is discretized by UDF using the explicit Euler method and executed at the end of each CFD time step to achieve real-time updates of speed and air pressure reaction. The translational motion of the moving parts of the arc-extinguishing chamber is controlled by the preset dynamic mesh motion model. The model drives the motion of the mesh nodes according to the velocity value obtained by real-time solution, so as to ensure the synchronization between the dynamic model and the dynamic mesh update. In each time step, the state variables such as displacement and velocity are transmitted to the flow field solver through UDF for subsequent result analysis.

The operating mechanism is coupled with the arc-extinguishing chamber through the pneumatic reaction force acting on the piston. Since the arc-extinguishing chamber has an initial charging pressure in the closed state, the effective pneumatic reaction force is calculated from the difference between the transient wall pressure and the initial pressure. The force is obtained by integrating the net pressure over the piston wall:

$$F_q = \oint_S (p(t) - p_0) \cdot n dS \quad (13)$$

The sum form of the discretized surface element is as follows:

$$F_q = \sum_{i=1}^N ((p_i(t) - p_0) \cdot A_{i,x}) \quad (14)$$

In the formula, $p(t)$ is the local wall pressure, $p_i(t)$ is the transient pressure of the i -th surface element, p_0 is the initial charging pressure of the arc-extinguishing chamber, dS is the wall surface element, and $A_{i,x}$ is the x -direction component of the corresponding area vector. In the UDF implementation, the pneumatic reaction force F_q is calculated at the end of each time step by integrating the net pressure $\Delta p_i = p_i(t) - p_0$ over the piston wall. The calculated force is then transferred to the operating-mechanism model to update the piston motion in the next time step.

2.3. Simulation Model of Fast Circuit Breaker Arc-Extinguishing Chamber

In this paper, the compressed air arc-extinguishing chamber is selected as the prototype of the 550 kV fast circuit breaker arc-extinguishing chamber. The structure diagram is shown in Figure 1, which is mainly composed of a contact system, compressed air chamber, nozzle and shielding cover. Figure 2 shows the arc simulation model of the arc-extinguishing chamber of the 550 kV fast circuit breaker. The two-dimensional axisymmetric structure is adopted, and the axial center of the arc-extinguishing chamber is taken as the symmetry axis. The radial velocity and the radial derivative of the physical quantity are set to zero. In this paper, based on the fluid dynamics calculation software (CFD), a geometric body is established and meshed to generate a dynamic mesh. The motion characteristics of the nozzle, compressor cylinder, and moving contact points are controlled by dynamic mesh technology combined with user-defined functions (UDF). The initial conditions are set to internal 0.6 MPa pressure, 300 K temperature and static airflow, and the pressure outlets on both sides are balanced with the external environment. In terms of electromagnetic boundary, the end of the static contact is set as the first type of zero potential boundary, the right side of the static arc contact is zero potential, and the second type of current density flux is applied at the end of the virtual contact. At the same time, the magnetic vector position of the end of the static contact, the end of the virtual contact and the arc extinguishing outdoor wall is set to zero, which is used to simulate the boundary effect away from the arc. The current is injected from the left side of the transparent contact to describe the arc characteristics of the 550 kV fast circuit breaker under different operating conditions.

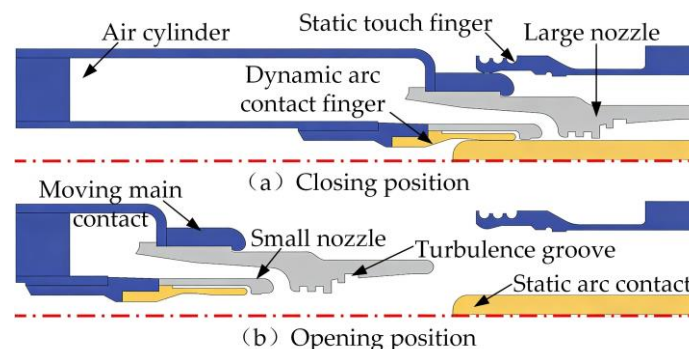


Figure 1. Structure diagram of compressed air arc-extinguishing chamber.

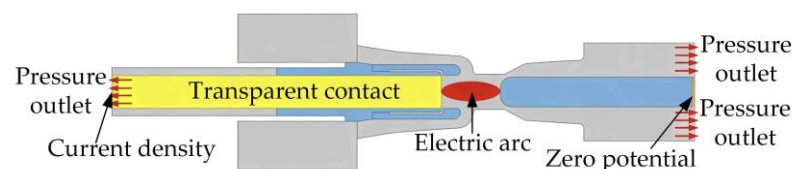


Figure 2. Simplified calculation model of 550 kV fast breaking arc-extinguishing chamber.

The accuracy of the co-simulation mode compared with the traditional circuit breaker simulation; the arc calculation of the fast circuit breaker faces two major challenges. First, the opening speed of the circuit breaker is significantly improved, resulting in a significant increase in the contact displacement per unit time, which puts forward more stringent requirements for the quality control of the dynamic mesh. Secondly, the transient changes in gas pressure and airflow characteristics in the arc-extinguishing chamber are more intense, especially in the current zero zone. The drastic changes in the physical field are extremely sensitive to the grid size and the calculation step size. The parameters and boundary conditions of the simulation model are shown in Table 2.

In the present model, a locally refined mesh strategy was adopted to improve the resolution of the arc region and the moving regions. The arcing region was divided using a structured mesh of $0.1\text{ mm} \times 0.1\text{ mm}$, while the other moving regions were divided using a structured mesh of $0.8\text{ mm} \times 0.8\text{ mm}$. The mesh size was selected by considering the sharp gradients of temperature, pressure, and velocity near the arc core, as well as the requirement of dynamic-mesh stability during high-speed contact motion. Since a systematic mesh-independence study was not completed in the present work, the numerical results are mainly used for comparative analysis among different structural schemes under the same mesh strategy, rather than for absolute prediction of breaking performance.

Instead of a single ‘fixed time step’ method, a hybrid control scheme of ‘fixed stroke + fixed time step’ is implemented through the UDF custom program: in the stage of high current arcing, ensure that the contact moves 0.1 mm per step, that is, a grid size; in the vicinity of the sensitive current zero zone, the time step is set to $0.1\text{ }\mu\text{s}$ to ensure that the transient changes in key parameters such as arc temperature, air pressure and airflow at the moment of current zero crossing can be accurately obtained.

Table 2. Main simulation parameters and boundary conditions.

Category	Parameter	Value/Description
Rated voltage	Voltage level	550 kV
Gas medium	Medium	SF ₆
Initial condition	Pressure	0.6 MPa
Initial condition	Temperature	300 K
Initial condition	Initial velocity	0 m/s
Current condition	Rated current	63 kA
Current condition	Frequency	50 Hz
Arcing condition	Long-arcing time	17 ms
Design target	Short-arcing target	8 ms
Geometry	Cylinder diameter	70, 80, 90 mm
Nozzle structure	Groove condition	With/without turbulence groove
Mesh	Arc region	$0.1\text{ mm} \times 0.1\text{ mm}$
Mesh	Other moving regions	$0.8\text{ mm} \times 0.8\text{ mm}$
Time step	Near current zero	$0.1\text{ }\mu\text{s}$
Boundary	Pressure outlet	Both sides balanced with external environment
Electromagnetic boundary	Potential/current boundary	Right end of stationary contact/Left end of transparent contact
Motion coupling	Dynamic mesh	UDF-based moving mesh
Material	Nozzle material	PTFE
Material	Contact material	Cu-W
Boundary condition	Outlet pressure	0.6 MPa

2.4. Numerical Implementation and Numerical Verification

To improve the reproducibility of the numerical simulation, the main solver settings, convergence criteria, dynamic-mesh strategy, and mechanism-coupling method are clarified in this section. As summarized in Table 3, a transient CFD solver is used in the calculation. The motion of the moving parts is realized by a UDF-based dynamic mesh, and the operating-mechanism model is updated at the end of each CFD time step. At each time step, the transient pressure on the piston wall is integrated to calculate the pneumatic reaction force. Then, the displacement and velocity of the moving parts are updated and

transferred to the flow-field solver for the next time step. The same numerical settings are used for all nozzle and cylinder configurations to ensure consistency in the comparative analysis.

The convergence criteria used in the transient calculation are also listed in Table 3. The residual thresholds are set to 10^{-4} for the continuity equation, 10^{-4} for the momentum equation, 10^{-6} for the energy equation, 10^{-4} for the turbulence equations, and 10^{-5} for the radiation equation. During each transient time step, the residuals of the governing equations are required to decrease below the prescribed thresholds. In addition, the main monitored variables, including cylinder pressure, nozzle airflow velocity, moving-contact displacement, and arc-core temperature, are checked to ensure stable transient convergence.

The turbulence model was selected to describe the engineering-scale high-speed gas-blast flow in the nozzle region with acceptable computational cost and numerical stability. Although this model cannot fully resolve all small-scale transient vortex structures, it is suitable for comparing the relative influence of different nozzle and cylinder configurations under the same numerical framework. The six-band P-1 radiation model is used to calculate radiation heat transfer in the arc region. The LTE assumption was adopted mainly for the high-temperature arc-core region during the high-current stage. Possible non-equilibrium effects near current zero are acknowledged as a limitation of the present model. Therefore, the present results are mainly used to compare the relative influence of different structural schemes on pressure, airflow, and temperature evolution, rather than to directly predict the final breaking capability.

Table 3. Numerical solver settings and convergence criteria.

Item	Setting
Solver type	Transient CFD solver
Dynamic mesh	UDF-based dynamic mesh
Mechanism coupling	Updated at the end of each CFD time step
Turbulence model	k- ϵ
Radiation model	Six-band P-1 model
Continuity residual	$<10^{-4}$
Momentum residual	$<10^{-4}$
Energy residual	$<10^{-6}$
Turbulence-equation residual	$<10^{-4}$
Radiation-equation residual	$<10^{-5}$

2.5. Numerical Verification and Applicability of the Mode

Due to the difficulty of obtaining direct experimental measurements of the internal arc temperature, pressure distribution, and transient flow field in a 550 kV fast circuit breaker, no direct prototype-test validation is available for the present model at this stage. Therefore, the purpose of this numerical model is not to provide an absolute prediction of the final breaking capability, but to compare the relative influence of different nozzle and cylinder configurations under the same numerical framework.

To improve the credibility of the numerical results, several numerical verification procedures were adopted. First, the same governing equations, boundary conditions, material properties, dynamic mesh strategy, and UDF-based coupling procedure were used for all investigated cases, which ensures that the comparison among different structures is consistent. Second, time-step sensitivity analyses were performed by monitoring the peak arc-core temperature, peak cylinder pressure, and maximum nozzle airflow velocity. Third, the convergence residuals and monitored variables, including cylinder pressure, moving-contact displacement, and arc-core temperature, were checked within each time step to ensure stable transient calculation. Finally, the pressure reaction force obtained by

surface integration was used to update the operating mechanism motion, and the calculated displacement and velocity were transferred back to the flow-field solver at each time step, ensuring the consistency of the mechanism–interrupter coupling.

It should be noted that the lack of direct experimental validation remains a limitation of this study. Therefore, the numerical results are mainly interpreted as relative trends among the investigated structural schemes. The conclusions regarding the turbulence groove and the cylinder diameter should be understood as comparative design guidance within the modeled conditions rather than as direct experimental proof of breaking performance. Future work will include prototype tests and comparison with measured contact motion and cylinder pressure to further validate the model.

3. High-Speed Opening Characteristics and Nozzle Shape and Compression Cylinder Matching Design

3.1. Nozzle Shape Matching Design

The design target of the fast circuit breaker is to achieve short arcing within approximately 8 ms. However, in order to evaluate the regulating effect of the nozzle turbulence groove under a more severe thermal load, a 17 ms long-arcing condition was selected as a conservative comparative case. Under long-arcing conditions, the arc energy input lasts for a longer time, the accumulation of high-temperature gas near the nozzle becomes more obvious, and the pressure attenuation during the late arcing and post-arc stages becomes more critical. Therefore, this condition is more suitable for observing whether the turbulence groove can enhance cold-hot gas mixing, improve the nozzle airflow field, delay pressure decay, and promote arc cooling. In this section, two nozzle structures with the same operating mechanism, boundary conditions, and current waveform are compared: one without a turbulence groove and the other with a turbulence groove. The dynamic characteristics of the operating mechanism and the flow-field characteristics of the arc-extinguishing chamber are then analyzed to evaluate the effect of the turbulence groove.

Figure 3 compares and analyzes the influence of whether the nozzle is provided with a turbulence groove on the displacement of the moving contact of the fast circuit breaker and the pressure gas reaction force of the arc-extinguishing chamber under the condition of long arc breaking. It can be seen from the curve that during the whole opening process, the displacement curves of the moving contact under the two structures with or without the turbulence groove basically coincide, and the displacement change trend is highly consistent with the numerical value, indicating that the setting of the turbulence groove has little effect on the contact motion characteristics. In terms of the pressure gas reaction force, the reaction force curves under the two nozzle structures almost overlap in the early stage of the opening, and there is only a slight difference in the late stage of the opening. The pressure gas reaction force with turbulence groove is slightly higher than that without turbulence groove, but the overall difference is not large, which does not have a significant impact on the dynamic response of the mechanism. It is necessary to focus on the regulation of the installation of turbulence grooves on the airflow field of the arc-extinguishing chamber and the arcing process.

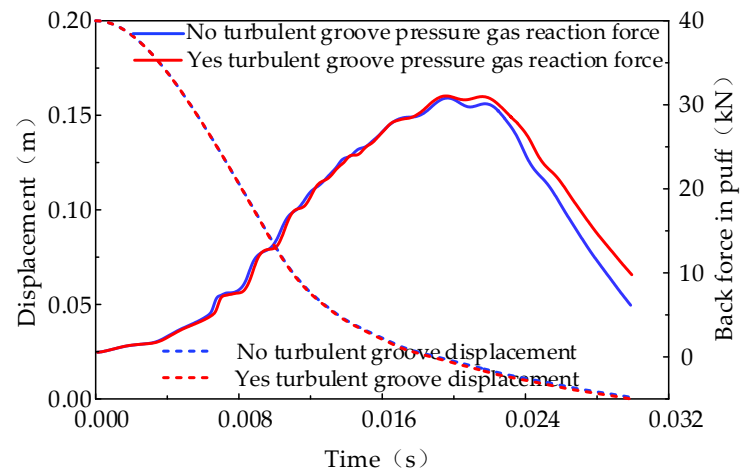


Figure 3. Moving-contact displacement and pneumatic reaction force with and without the nozzle turbulence groove under the 17 ms long-arcing condition.

Figure 4 shows the pressure change curve of the compression cylinder with or without turbulence groove under long arcing condition. It can be seen from the calculation results that compared with the nozzle without turbulence groove, the pressure rise rate in the compression cylinder after the installation of turbulence groove is slightly accelerated, and the peak value is slightly improved, and the pressure drop speed of the compression cylinder is obviously delayed at the critical moment of long arc extinction and the post-arc recovery stage, indicating that the turbulence groove promotes the rapid diffusion of arc energy and local heat exchange efficiency by enhancing the gas turbulence intensity, resulting in a more concentrated gas thermal expansion process. Figure 5 shows the pressure distribution cloud diagram of 1 ms before the second zero-crossing point of the current with or without the nozzle turbulence groove. Compared with the turbulence groove, the distribution range of the high pressure area in the upstream of the nozzle and the low pressure area in the downstream of the nozzle is significantly expanded after the turbulence groove is added. This phenomenon may be due to the fact that the turbulent trough enhances the turbulent mixing effect of the airflow, which intensifies the energy dissipation of the upstream high-speed airflow, thus forming a wider high-pressure agglomeration area. At the same time, the forward movement of the flow separation point induced by turbulence and the evolution of the vortex structure in the downstream lead to the expansion of the coverage of the low pressure zone.

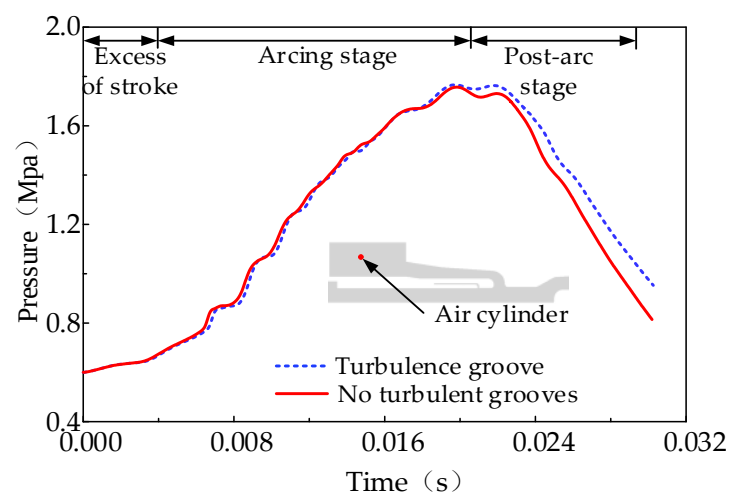


Figure 4. Pressure change curve of compression cylinder with or without nozzle turbulence groove.

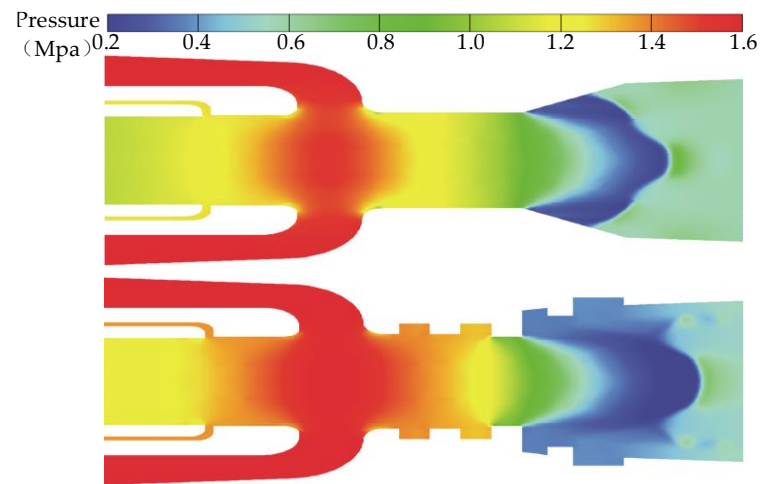


Figure 5. Pressure distribution at 1 ms before the second current zero with and without the nozzle turbulence groove.

Further combined with the axial airflow velocity change curve at 1 ms before the second zero-crossing point of the current in Figure 6, it can be seen that compared with the non-turbulence groove condition, the addition of turbulence groove increases the air-flow velocity in the nozzle area, which helps to promote the rapid dissipation of arc energy in the nozzle area, and may provide more favorable flow field conditions for the rapid cooling of the arc and the recovery of the dielectric strength.

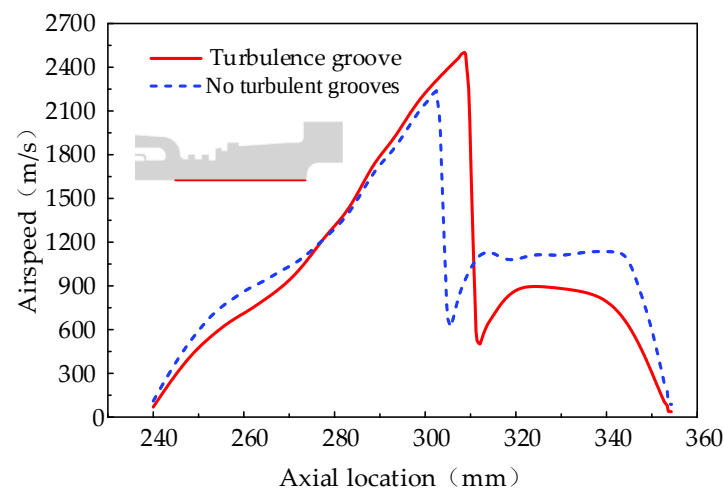


Figure 6. Axial airflow velocity along the nozzle centerline at 1 ms before the second current zero.

Further combined with the temperature distribution cloud map of Figure 7 and the radial temperature change curve of the upstream of Figure 8 nozzle, the temperature field characteristics of the arc-extinguishing chamber are improved after the installation of the turbulence groove. The recirculation zone formed in the turbulence groove promotes more sufficient heat exchange between the cold and hot airflow by prolonging the contact time between the cold airflow and the high temperature arc. According to the cloud map in Figure 7, the temperature field characteristics of the arc-extinguishing chamber are improved after the installation of the turbulence groove. The streamlines downstream of the nozzle become more dense, indicating that the turbulent kinetic energy is enhanced, which in turn promotes the penetration of the low-temperature airflow into the core area of the arc and accelerates the radial thermal diffusion. The recirculation zone formed in the turbulence groove promotes more sufficient heat exchange between the cold and hot

airflow by prolonging the contact time between the cold airflow and the high temperature arc.

The radial temperature curve in Figure 8 shows that, after the turbulence groove is introduced, the maximum temperature in the arc-core region decreases from 32.5 kK to 31.4 kK. This corresponds to an absolute reduction of 1.1 kK and a relative reduction of approximately 3.38%. Therefore, the decrease in the peak arc-core temperature is moderate but quantifiable.

In the range of 0–4 mm, the measuring position is close to the arc core, where Joule heating and high-temperature plasma dominate the thermal field, so the temperature remains at a high level. In the range of 4–6 mm, the curve enters the thermal transition region between the arc core and the surrounding cold gas flow. Strong radial heat conduction and turbulent diffusion occur in this region, leading to a rapid and approximately linear decrease in temperature. After the turbulence groove is added, the intermediate-temperature transition region becomes wider and the radial temperature gradient becomes gentler, indicating enhanced cold-hot gas mixing and radial heat diffusion. Beyond approximately 8 mm, the measuring position is outside the main arc-core and thermal transition regions. The gas temperature is mainly governed by the surrounding low-temperature airflow, and the radial temperature gradient becomes small. Therefore, the curve tends to a quasi-stable low-temperature level after 8 mm.

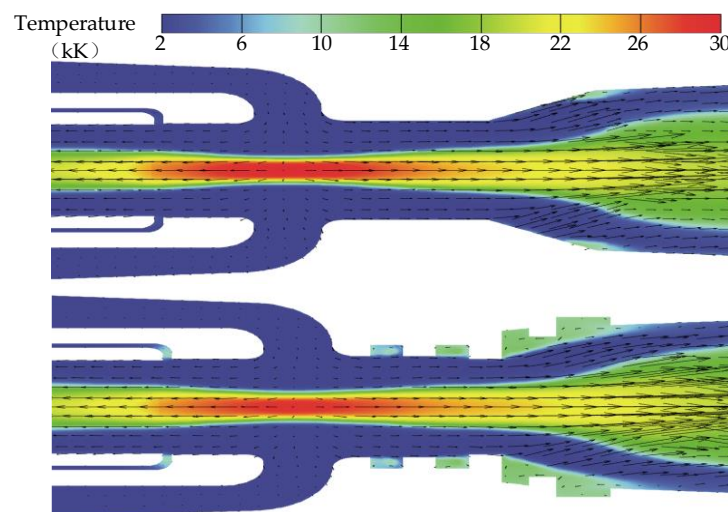


Figure 7. The temperature distribution cloud chart of 1 ms before the second zero-crossing point of the current under the turbulence groove with or without nozzle is shown.

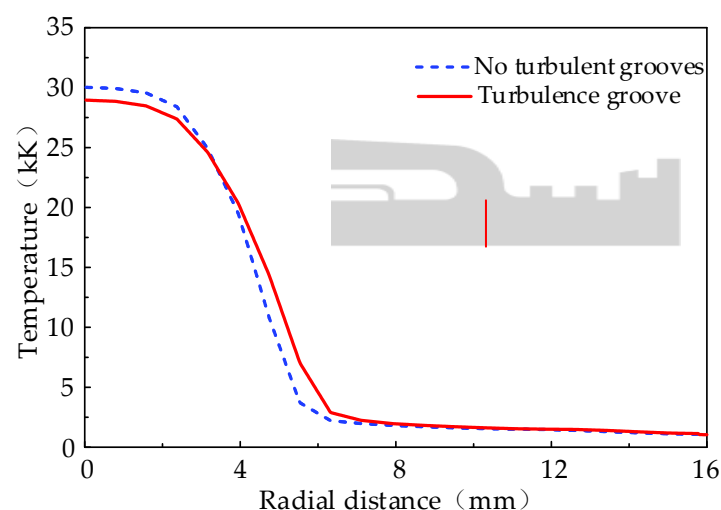


Figure 8. Radial temperature distribution upstream of the nozzle at 1 ms before the second.

To further quantify the effect of the turbulence groove, the main indicators extracted from Figures 4–8 are summarized in Table 4. The results show that the turbulence groove has a limited influence on the overall pressure peak, with the peak cylinder pressure increasing from approximately 1.74 MPa to 1.78 MPa. However, the pressure retention in the post-arc stage is improved more clearly. At approximately 28 ms, the cylinder pressure increases from about 1.00 MPa without the turbulence groove to about 1.15 MPa with the turbulence groove. In addition, the time at which the cylinder pressure drops below 1.2 MPa is delayed by approximately 1.0 ms, indicating that the turbulence groove helps maintain the gas-blowing pressure during the post-arc stage.

Table 4. Quantitative comparison of nozzle structures with and without turbulence groove.

Indicator	No Turbulence Groove	Turbulence Groove	Change
Peak cylinder pressure	1.74 MPa	1.78 MPa	+2.3%
Cylinder pressure	1.00 MPa	1.15 MPa	+15.0%
Time when pressure drops below 1.2 MPa in post-arc stage	26.5 ms	27.5 ms	1.0 ms
Maximum axial airflow velocity	2250 m/s	2500 m/s	+11.1%
Maximum arc-core temperature	30.0 kK	29.0 kK	−3.3%
Radial thermal transition region	narrower	wider	radial heat diffusion enhanced

The axial airflow velocity is also increased near the nozzle region. As shown in Figure 6, the maximum axial airflow velocity increases from approximately 2250 m/s to 2500 m/s after the turbulence groove is introduced, corresponding to an increase of about 11.1%. Meanwhile, the radial temperature distribution in Figure 8 shows that the maximum arc-core temperature decreases from approximately 30.0 kK to 29.0 kK, corresponding to a reduction of about 1.0 kK, or 3.3%. These quantitative indicators show that the turbulence groove improves the local flow-field and thermal conditions without significantly changing the mechanical motion of the moving contact.

The physical mechanism of the turbulence groove can be explained from the coupling between the local flow structure and arc heat transfer. The turbulence groove does not mainly change the moving-contact motion, as indicated by the almost coincident displacement curves. Instead, it modifies the local airflow distribution near the nozzle. The groove induces a recirculation zone, which prolongs the interaction time between the cold gas flow and the high-temperature arc region. As a result, cold-hot gas mixing is enhanced, and the radial diffusion of thermal energy from the arc core to the surrounding low-temperature gas is promoted. This explains why the intermediate-temperature transition region becomes wider and the radial temperature gradient becomes gentler after the groove is introduced. Therefore, the influence of the turbulence groove should be understood as a coupled improvement in flow redistribution, radial heat diffusion, and pressure retention, rather than only as a decrease in the peak arc-core temperature.

In summary, the turbulence groove mainly improves the local flow-field and thermal characteristics. The pressure peak is only slightly increased, but the post-arc pressure retention is improved, and the pressure drop below 1.2 MPa is delayed by approximately 1.0 ms. The maximum axial airflow velocity increases by about 11.1%, and the maximum arc-core temperature decreases by about 3.3%. These results indicate that the turbulence groove enhances cold-hot gas mixing, radial heat diffusion, and post-arc pressure

retention, thereby providing more favorable flow-field conditions related to arc cooling and dielectric recovery.

3.2. Press Compression Cylinder Size Matching Design

Appropriately increasing the volume of the compression cylinder can ensure the effective breaking of the long arc. Based on the original compression cylinder diameter length of 70 mm, this paper simulates the two cases of the compression cylinder diameter increasing by 10 mm and 20 mm respectively. According to the comparative analysis results of Figure 9, the diameter of the compression cylinder ($D_c = 70$ mm, 80 mm, 90 mm) has a significant effect on the moving contact displacement of the fast circuit breaker and the pressure reaction force of the interrupter. In the early stage of the movement, the displacement curves of the moving contact under different compression cylinder diameter are basically coincident, indicating that the driving force of the mechanism is dominant in the movement at this time, and the influence of the pressure reaction force has not yet appeared. As the opening process enters the middle and late stages, the displacement curve of the moving contact under the condition of $D_c = 90$ mm obviously tends to be gentle, and the movement speed decreases, while the displacement curves of $D_c = 70$ mm and 80 mm are still relatively close, with little difference. This is because as the diameter of the compression cylinder increases, its area of action increases accordingly, resulting in a significant increase in the pressure gas reaction force. Especially after the driving force is greatly reduced in the buffer stage, the pressure gas reaction force has a more prominent inhibitory effect on the movement of the moving contact. Therefore, under the condition of large compression cylinder diameter, the air pressure reaction force becomes the key factor affecting the dynamic response of the moving contact, which will reduce the moving speed of the moving contact to a certain extent. However, when the diameter is small, the driving force of the operating mechanism still dominates the movement process, which will not significantly affect the moving speed of the moving contact.

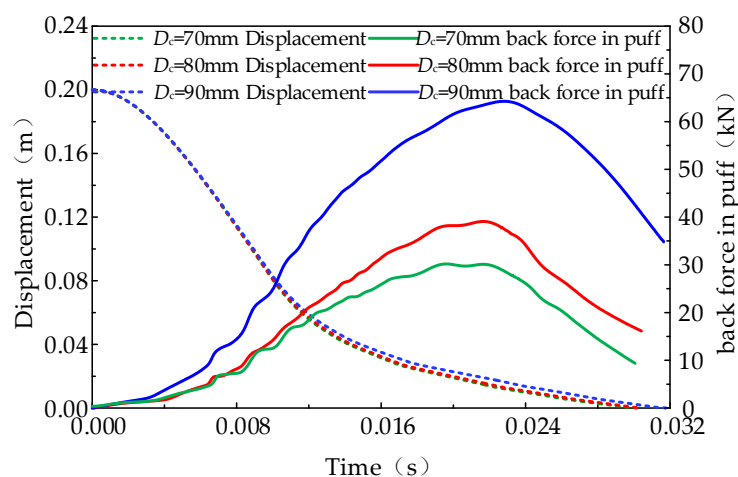


Figure 9. Curves of moving contact displacement and air pressure reaction force under different compression cylinder diameter.

Figure 10 shows the variation in compression cylinder pressure under three different compression cylinder diameter D_c under long arcing conditions. The results show that D_c has a significant influence on the establishment and attenuation process of the pressure of the compression cylinder.

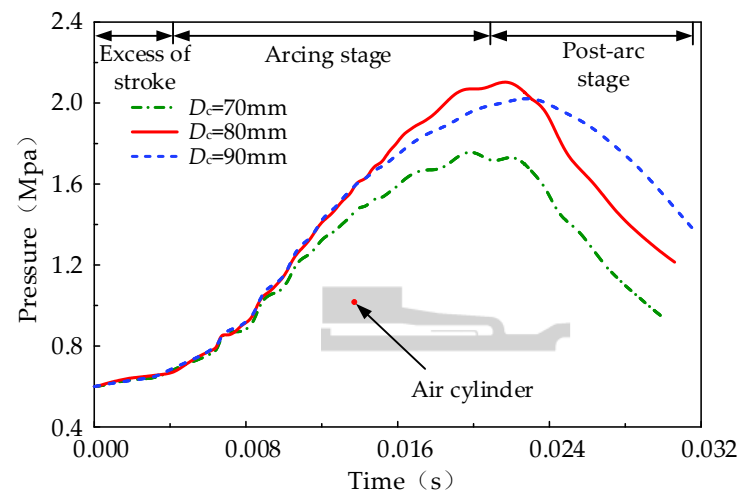


Figure 10. Cylinder pressure evolution for different cylinder diameters under the long-arcing condition.

The influence of the compression cylinder diameter on the arcing process is governed by the balance between gas storage capacity and mechanism dynamic response. When $D_c = 70$ mm, the effective gas volume is relatively small, so the pressure build-up and gas-blowing capability are insufficient during the long-arcing stage. When D_c increases to 90 mm, the larger piston area increases the pneumatic reaction force. In the middle and late stages of opening, this reaction force suppresses the piston motion and reduces the effective compression speed, which weakens the pressure accumulation in the compression cylinder. Therefore, a larger compression cylinder diameter does not necessarily produce a higher pressure. In the investigated cases, $D_c = 80$ mm provides a better compromise between gas supply and mechanical motion, allowing more effective pressure build-up and arc cooling near the critical arcing stage.

As shown in Figures 11 and 12, the compression-cylinder diameter has a clear influence on the temperature distribution in the arc-extinguishing chamber. When $D_c = 70$ mm, the arc-core temperature is the highest at about 31.4 kK, and the high-temperature region extends over a wider radial and axial range, indicating insufficient gas-blowing cooling. When $D_c = 90$ mm, the temperature is lower than that of $D_c = 70$ mm but still higher than that of $D_c = 80$ mm, showing an intermediate cooling effect. This is because the larger cylinder diameter increases the pneumatic reaction force and weakens the effective compression process. In comparison, $D_c = 80$ mm gives the lowest arc-core temperature, about 29.0 kK, and shows faster radial temperature attenuation and lower axial temperature. Therefore, $D_c = 80$ mm provides the most favorable arc-cooling performance among the three investigated cases.

Overall, the arcing behavior in the fast circuit breaker is controlled by the coupled interaction among contact motion, pneumatic reaction force, pressure build-up, nozzle airflow, and arc heat transfer. The turbulence groove mainly affects the local flow-field structure by inducing recirculation and enhancing cold-hot gas mixing, thereby promoting radial heat diffusion from the arc core. In contrast, the compression cylinder diameter mainly affects the pressure build-up through the coupling between gas volume and piston motion. A small compression cylinder diameter leads to insufficient gas supply, whereas an excessively large diameter increases the pneumatic reaction force and suppresses the opening motion. Therefore, the arc-cooling performance is not determined by a single factor, such as gas volume or peak velocity, but by the coordinated matching of the operating mechanism and the arc-extinguishing chamber.

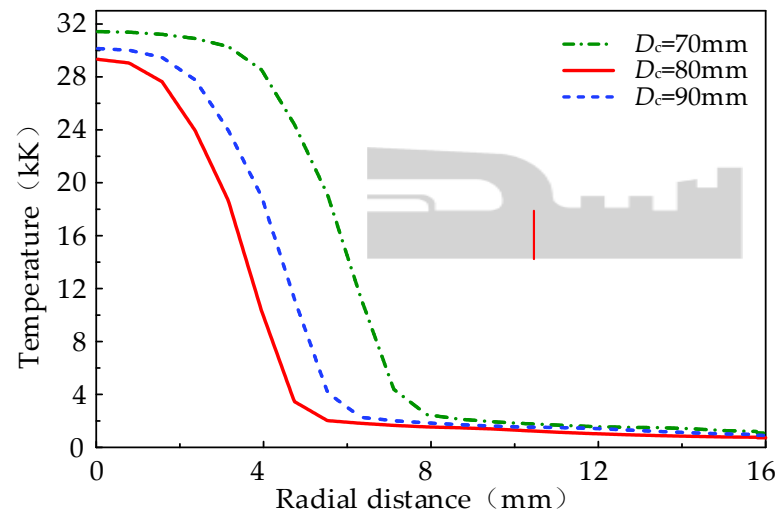


Figure 11. Radial temperature curve of nozzle upstream under different compression cylinder diameter.

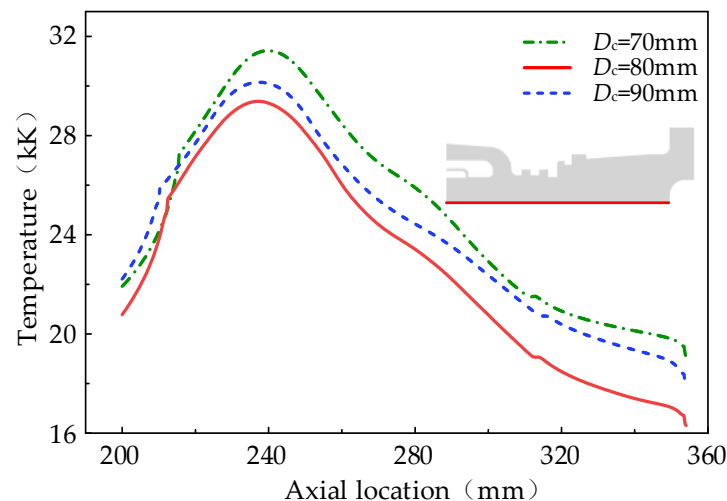


Figure 12. Axial position temperature curve under different compression cylinder diameter.

4. Conclusions

Based on the multiphysics co-simulation model of the operating mechanism and the arc-extinguishing chamber, this chapter studies the cooperative regulation relationship between the mechanism dynamics and the arc characteristics of the arc-extinguishing chamber during the high-speed opening process of the 550 kV fast circuit breaker, and completes the optimization matching of the key structural parameters of the arc-extinguishing chamber.

1. The turbulence groove increases the pressure rise rate and peak value in the compression cylinder by enhancing the gas turbulence intensity. More importantly, in the critical period of long arc extinction and the post-arc recovery stage, the turbulence groove can effectively slow down the pressure drop rate. This indicates that the turbulence groove promotes the rapid diffusion of arc energy and local heat exchange, making the gas thermal expansion process more concentrated, providing a continuous and stable pressure guarantee for arc extinguishing.
2. The flow field structure of the arc-extinguishing chamber is changed by adding a turbulence groove. By inducing a recirculation zone in the groove, the contact time between the cold airflow and the high temperature arc is prolonged, and the deep

exchange of cold and hot airflow is realized. This mechanism significantly improves the airflow velocity and radial thermal diffusion efficiency in the nozzle area, realizes the synergistic effect of high-speed cooling, high-temperature suppression and low-temperature expansion, and creates an optimized flow field environment for the efficient dissipation of arc energy and the recovery of dielectric strength.

3. There is a nonlinear coupling equilibrium point in the influence of the diameter of the compression cylinder on the breaking performance: the smaller diameter of 70 mm leads to weak arc blowing strength due to insufficient effective volume; the larger diameter of 90 mm inhibits the driving performance of the mechanism and the speed of the piston due to the overload of the pressure gas reaction force, which hinders the pressure accumulation. For the compression-cylinder diameter, $D_c = 70$ mm leads to insufficient gas-blowing pressure, while $D_c = 90$ mm increases the pneumatic reaction force and suppresses the motion of the moving contact in the middle and late stages of opening. Among the three investigated cases, $D_c = 80$ mm provides a better balance between gas storage capacity, pneumatic reaction force, pressure build-up, and mechanical response. Therefore, $D_c = 80$ mm can be regarded as a suitable matching diameter within the investigated range of 70–90 mm, rather than a global optimum. A broader parametric study with smaller diameter intervals will be required in future work to determine the global optimum cylinder diameter.
4. It should be noted that a systematic mesh-independence verification was not included in the present study. Therefore, the numerical results should be interpreted mainly as relative comparisons among the investigated nozzle and cylinder configurations. Future work will include a detailed mesh-independence and time-step sensitivity analysis to further improve the quantitative reliability of the model.

Author Contributions: B.X.: Conceptualization, investigation, and writing—original draft; S.W., T.Z., L.Z., Q.Z.: Funding acquisition, writing—review and editing, and resources; J.W., Q.S., J.Z.: Methodology and supervision; X.L.: Software, validation, data curation, and visualization. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is based on project No. B311DS250005, supported by Electric Power Research Institute of State Grid Zhejiang Electric Power Co., Ltd.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Shaoan Wang, Tianbo Zhang, Jianwei Wei, Qingchao Sun, Bowen Xu, Lumin Zhao, Qijie Zhu, Jianlei Zhao, and Xiangwei Li were employed by the company State Grid Zhejiang Electric Power Co., Ltd. Electric Power Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from project No. B311DS250005, supported by Electric Power Research Institute of State Grid Zhejiang Electric Power Co., Ltd. The funder had the following involvement with the study: funding acquisition, writing—review and editing, and resources. The authors declare that this study received funding from project No. B311DS250005, supported by Electric Power Research Institute of State Grid Zhejiang Electric Power Co., Ltd. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

References

1. Zhang, H. Short circuit current limiting technology and engineering application based on 252 kV fast vacuum circuit breaker. *Power Syst. Technol.* **2022**, *46*, 2850–2857.

2. Han, X.; Sun, X.; Chen, H. The overview of development of UHV AC transmission technology in china. *Proc. CSEE* **2020**, *40*, 4371–4386+4719.
3. Zhong, J.; Chen, G.; Tan, S. Key technology and development trend of high-voltage switchgear. *High Volt. Eng.* **2021**, *47*, 2769–2782.
4. Ma, K.; Yao, X.; Zhang, L. Development and testing of a 252 kV/2500 A-40 kA multi-break bus-coupler fast vacuum circuit breaker. *Energies* **2021**, *14*, 4285.
5. Song, Y.; Lin, X.; Xu, J. Interruption performance of C₄F₇N/CO₂ gas in High-voltage circuit breaker. *High Volt. Eng.* **2023**, *49*, 971–981.
6. Lowke, J. Two-dimensional calculation of properties of arcs in high speed flow. In Proceedings of the VII International Conference on Gas Discharges and their Applications, London, UK, 31 August–3 September 1982; pp. 20–25.
7. Ragaller, K.; Egli, W.; Brand, K. Dielectric recovery of an axially blown SF₆-arc after current zero, Part I experimental investigation. *IEEE Trans. Plasma Sci.* **1982**, *10*, 154–162.
8. Ragaller, K.; Egli, W.; Brand, K. Dielectric recovery of an axially blown SF₆-arc after current zero, Part II theoretical investigation. *IEEE Trans. Plasma Sci.* **1982**, *10*, 141–153.
9. Yan, J.; Fang, M.; Hall, W. The development of PC based CAD tools for auto-expansion circuit breaker design. *IEEE Trans. Power Deliv.* **1999**, *4*, 176–181.
10. Pei, Y.; Zhong, J.; Zhang, J. A comparative study of arc behaviour in an auto-expansion circuit breaker with different arc durations. *J. Phys. D Appl. Phys.* **2014**, *47*, 335201.
11. Li, X.; Jia, S.; Zhang, B. Research and application on physical parameters calculation and behavior simulation of gas switching Arc. *High Volt. Eng.* **2020**, *46*, 757–771.
12. Rong, M.; Wu, Y.; Yang, F. Review on the simulation method of non-equilibrium arc plasma during current zero period in the circuit breaker. *Trans. China Electrotech. Soc.* **2013**, *49*, 64–68.
13. Jin, L.; Dong, X.; Yan, S. Impact of nozzle structure on short arc time of half-self-extinguish SF₆ circuit breaker. *High Volt. Appar.* **2017**, *32*, 1–12+23.
14. Zhong, J.; Lin, X.; He, R. The parallel computation simulation of the extinguishing arc performance in the self-extinguished SF₆ circuit breaker *High Volt. Appar.* **2006**, *42*, 154–159.
15. Lin, X.; Li, X.; Wang, F. Dielectric recovery characteristics of SF₆ circuit breaker considering contact burning loss. *High Volt. Engineering* **2014**, *40*, 3125–3134.
16. Ma, Z.; Zhao, W. Modeling and simulation on opening characteristic of spring operating mechanism for High Voltage SF₆ circuit breaker. *High Volt. Appar.* **2017**, *53*, 109–115.
17. Guo, X.; Liang, D.; Huang, Z. Research on motion parameters of electromagnetic repulsion mechanism based on multi-field coupling. *High Volt. Eng.* **2022**, *48*, 626–635.
18. Zhang, Z. Design and research on buffer structure of hydraulic spring operating mechanism. *Pneumatics* **2018**, *04*, 115–119.
19. Wei, J.; Lin, X. Pressure Character and Mechanism Character Coupling Computation of SF₆ High Voltage Circuit Breaker. *Proc. CSEE* **2007**, *27*, 110–116.
20. Wang, W.; Yan, X.; Li, X.; Guo, D.; Geng, Z. Investigation of the Arc Characteristics in a Nozzle with C₄F₇N/CO₂ Mixtures. *Energies* **2024**, *17*, 4593.
21. Liu, T.; Sun, H.; Li, G.; Zhang, Y.; Wang, J.; Xiao, J.; Lu, Y.; Niu, C.; Wu, Y. Decay characteristic of gas arc in C₄F₇N/N₂ and C₄F₇N/CO₂ gas mixture by Thomson scattering. *J. Phys. D: Appl. Phys.* **2025**, *58*, 045203.
22. Deng, J.; Zhang, B.; Cao, M.; Wang, G.; Chen, S.; Wang, Z.; Li, X.; Murphy, A.B. Radiation properties of [C₄F₇N-CO₂-O₂]-PTFE-Cu mixtures at high temperatures and pressures for high-voltage circuit breakers. *J. Phys. D Appl. Phys.* **2025**, *58*, 015206.
23. Wang, G.; Zhang, B.; Cao, M.; Deng, J.; Shi, Y.; Li, B.; Li, X.; Murphy, A.B. Two-temperature thermodynamic and transport properties of C₄F₇N-CO₂-O₂ mixture as an arc-extinguishing gas. *J. Phys. D Appl. Phys.* **2025**, *58*, 165502.
24. Wang, W.; Yan, X.; Wang, H.; Gao, K. Comparative studies of C₄F₇N-based gas mixtures as the eco-friendly alternative to SF₆ for interrupting applications. *High Volt.* **2025**, *10*, 228–242.
25. Lee, J.; Lee, J. Turbulent effort of SF₆ thermal plasma inside a puffer-assisted self-blast chamber. *Vacuum* **2012**, *86*, 1522–1527.
26. Gonzalez, J.; Freton, P.; Reichert, F. Turbulence and magnetic field calculations in high-voltage circuit breakers. *IEEE Trans. Plasma Sci.* **2012**, *40*, 936–945.
27. Wang, F.; Zhao, Y.; Zhang, B. Numerical Calculation and Analysis of the Breaking Process of 10 kV Jet Fuse. *High Volt. Apparatus* **2024**, *60*, 191–200.

28. Wu, Y.; Rong, M.; Yang, F. Introduction of 6-band P-1 radiation model for numerical analysis of three-dimensional air arc plasma. *Acta Phys. Sin.* **2008**, *57*, 5761–5767.
29. Zou, H.; Li, X.; Zhong, J. Co-simulation of liquid-machine-gas machine of 550 kV fast circuit breaker. *High Volt. Eng.* **2024**, *50*, 1003–1013.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.