Influence of chamber structure on arc quenching in multigap system

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Abstract: In order to improve the arc quenching ability of the multigap system, it is important to know the principle of arc quenching and how the chamber structure affects the arc development process in the multigap system. In this study, the two-dimensional geometric model of the multigap system is established based on the magnetohydrodynamics theory in COMSOL multiphysics simulation platform. The principle of arc quenching in the multigap system is explained in detail by analysing the physical characteristics of the arc in the multigap system. The simulation result shows that the arc is compressed at large scales in the semi-closed chambers of the multigap system, which results in an instantaneous temperature rise of the arc, thus, forming the self-expanding airflow. The strong self-expanding airflow cuts off the arc channel and blocks the energy supply of the arc. The influence of the chamber structure on arc quenching in the multigap system is manifested in the fact that proper improvement of the width and depth of the chamber subserves arc cooling, the reduction of the deflection angle and the increment of the number of the chambers are conducive to arc extinction.

1 Introduction
Lightning trip-out is a severe problem that threatens power supply. Almost 40–70% outages on power networks are caused by lightning [1–3]. The power frequency arc established after lightning flashover is the main reason that gives rise to short circuit fault and lightning trip-out.

To solve the problem caused by follow-up power frequency arc, some scholars and companies began to carry out studies of arc-extinguishing equipment. In addition to the most commonly used line arresters, there are some other devices including a kind of arcing horn device that can generate substantial dielectric gas to extinguish the short circuit arc [4, 5], the metal oxide varistor, which is able to suppress arc development [6], a type of arc-quenching lightning protection gap, which is designed to blow high-speed jet stream to quench power frequency arc [7–9], electrical installation using magnetic force to elongate and truncate arc [10]. However, these devices have problems such as the lack of surge absorption capability, limited gas capsules, and the complex structure, which may cause equipment failure.

At present, the multigap system (MGS) is mostly used in the field of circuit breakers and switches. Liu et al. [11] pointed out that MGS can balance electric field distribution and ensure the breakdown stability of gap. Also, as is mentioned in [12], changing the long arc into many series of short arcs is conducive to extinguishing the arc. Combined with the above advantages, the MGS is applied in the field of lightning protection of overhead lines with the purpose of solving the problem of arc establishing caused by lightning strokes.

As a matter of fact, in recent years, some research institutions around the world have done researches on MGS and lightning protection devices based on MGS [13–15]. These kinds of devices are generally installed parallelly beside the insulator or installed outside the insulator in screw type. The volt-second characteristic curve of such devices are at least 15% lower than that of the insulator, once lightning overvoltage happens, MGS will first establish a flashover to protect the insulator from being damaged. After releasing the lightning impact energy to the ground, the MGS can extinguish power frequency arc before the relay protection, thus preventing lightning tripping. Compared with the lightning protection devices introduced above, MGS-based devices are simple structured, easy made, low cost, and have a relatively long maintenance period [16].

Studies have shown that ‘zero quenching’ and ‘impulse quenching’ are two basic modes of arc quenching in MGS [17]. In the former case, the arc current will stop the flow at zero-crossing and the latter, the arc development process will be deeply suppressed in the impulse arc stage. In contrast, the ‘impulse quenching’ has obvious advantages such as shorter extinguishing time and higher current interrupting threshold. However, the arcing time of currently used MGS-based lightning protection devices is designed to be <10 ms since ‘zero quenching’ dominates the arc-quenching process. So, in this case, the devices still cannot avoid the erosion of the arcing chambers and the electrodes. In order to optimise the effect of arc quenching in MGS, it is necessary to study the mechanism of ‘impulse quenching’ in MGS and make full use of it.

The special spatial arrangement and chamber structure of MGS are the key points to affect the impulse arc quenching performance. The main purpose of this study is to analyse the arc establishing and extinguishing principle of impulse arc quenching in MGS and discuss the arc development process under the influence of structural differences. The two-dimensional (2D) geometry model of arc extinguishing by MGS was built based on the theory of magnetohydrodynamics (MHD) [18] on the COMSOL Multiphysics simulation platform. Relevant arc establishing and extinguishing process were analysed quantitatively. The results provide a reference for the improvement and optimisation of the MGS based arc-quenching lightning protection device.

2 Arc development process based on MHD model
2.1 Assumptions
The mathematical model of electric field coupled fluid and heat transfer is established in this study. The following are the main assumptions [19–21]:
(i) The arc plasma is thermal plasma which satisfies the local thermodynamic equilibrium conditions.
(ii) The arc is a high-temperature form of air, its thermal conductivity, viscosity coefficient, electrical conductivity, heat capacity at constant pressure and radiation heat loss are the single-valued functions of temperature.

(iii) The arc is assumed to be compressible laminar flow.

(iv) The arc satisfies the gas state equation, the arc density is a function of pressure and temperature.

(v) The effects of the Lorentz force and viscous dissipation on the fluid flow are ignored.

(vi) The viscous heating is ignored.

2.2 Control equations

The arc plasma satisfies the Navier–Stokes equation and the current conservation equation in MGS with the above assumptions. The control equations are as follows:

Mass conservation equation:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]  \hspace{1cm} (1)

Momentum conservation equation:
\[ \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{J} \times \mathbf{B} \]  \hspace{1cm} (2)

Energy conservation equation:
\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_v u \cdot \nabla T - \nabla \cdot (k \nabla T) = \frac{\partial}{\partial t} \left[ \frac{5}{2} \rho k_b T \right] \nabla \cdot \mathbf{J} + E \cdot \mathbf{J} + Q_{rad} \]  \hspace{1cm} (3)

Gas state equation:
\[ p = \rho RT \]  \hspace{1cm} (4)

Current conservation equation:
\[ \nabla \cdot \mathbf{J} = - \frac{\partial \rho_e}{\partial t} \]
\[ \mathbf{J} = \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_e \]  \hspace{1cm} (5)

where \( \rho, t, \) and \( \mathbf{u} \) are the fluid density, time, and velocity vector, respectively, \( p, \mathbf{I}, \) and \( \mu, \) respectively, represent the absolute pressure, second-order unit tensor and the viscosity coefficient; \( C_p, k, \) and \( k_b \) are the heat capacity at constant pressure, the thermal conductivity and the Boltzmann constant, respectively; \( q, \mathbf{J}, \) and \( \mathbf{E} \) are the unit charge, current density, and electric field intensity, respectively; \( Q_{rad} \) and \( R \) represent the radiation heat loss and universal gas constant; \( \rho_e \) and \( \sigma \) represent the electric charge density and electrical conductivity; \( \mathbf{D} \) and \( \mathbf{J}_e \) denote the electric displacement vector and density of external electric current; and \( V \) indicates the potential.

2.3 Arc development process

On the right-hand side of (3), the first term is the term of electron enthalpy transfer, which represents the convection heat transfer of plasma, the second term is the term of joule heat and the third term is the term of the total volume radiation. Of the three terms, Joule heat is the most important reason for the temperature rise of the arc, and the conductivity is a single function of temperature. This accounts for the reason why the air gap generates an arc under the effect of lightning impulse and power frequency.

Meanwhile, convection heat dissipation, conduction heat dissipation, and radiation heat dissipation are three important ways to reduce the arc temperature. The radiation heat dissipation is related to the arc temperature so it cannot be controlled artificially, whereas the convection heat dissipation and conduction heat dissipation can be controlled by adjusting the chamber structure to extinguish the arc in the MGS.

3 Simulation analysis

3.1 Simulation conditions

The lighting protection device shown in Fig. 1 consists of MGS and series gap. During the actual installation, the fittings of MGS is adjusted to control the length of the series gap, by this way, the lighting protection device is able to meet the insulation coordination with the insulator, thus, the lightning impulse flashover will occur on the side of the device, avoiding damage of the insulator. In this study, we mainly discuss the development of arc in MGS, so the influence of the series gap and the skirt border of the device are ignored. A 2D internal geometric model of the MGS is established as shown in Fig. 2.

3.2 Simulation setting

In Fig. 2, the material in yellow, blue and grey are electrodes, insulation material, and air, respectively. The heat capacity at constant pressure, the electrical conductivity, the thermal conductivity, and the density of electrodes are set to 4403/(kg × K), 1.12 × 10^3 S/m, 76.2 W/(m × K) and 7870 kg/m³, respectively. The plots of electrical conductivity and thermal conductivity against temperature are shown in Figs. 3 and 4, respectively. The density, heat capacity at constant pressure, thermal conductivity, dynamic viscosity, electrical conductivity, radiation coefficient of the air in
The thermal conductivity, heat capacity at constant pressure, and density of the insulation material (improved nylon material) are set to 0.26 W/(m·K), 2000 J/(kg·K), and 1000 kg/m³ respectively. The relative dielectric constant is set at 1 in the chambers and external space. The initial temperature of the external space is also 293.15 K; there is natural convection heat dissipation between the airflow and the external space, the natural convection heat dissipation coefficient is 2.5 W/(m²·K); there is no slippage at solid boundaries; there is no normal current density at the boundaries of insulation material; the initial velocity of the airflow is set to 0 m/s; pressure of the airflow and the external space is defined as 0.1 MPa at one standard atmosphere. Ground electrode potential is defined as V = 0. Three times lightning impulse and power frequency current are defined to flow through the high-voltage electrode, among which power frequency is set at 0.5 kA and three times lightning impulse is set at the amplitude of 18, 14.5, and 12.5 kA, respectively, in the 10/350 μs lightning current waveform. Time interval of the simulation is defined as 0.01 ms. In order to ensure the effectiveness of lightning current function in the calculation process, the lightning waveform is processed smoothly by a continuous second derivative as shown in Fig. 5.

### 3.3 Simulation result and analysis

#### 3.3.1 Generation of self-expanding airflow:
When the lightning impulse breaks through the chambers, the air in each chamber is heated and forms a huge joule heat. The chamber inside MGS is narrow and surrounded by insulation materials, so the air cannot conduct heat dissipation to the external space sufficiently, hence, resulting in heating up sharply of the air in a very short time. The instantaneous rise in temperature of the air in the chamber is accompanied by a sharp decrease in air density. According to (1), air fluid must generate velocity flux externally at this time to form the self-expanding airflow.

In the vents of the half-closed chambers in MGS, tremendous velocity fluxes are generated. Fig. 6 shows the velocity distribution at the peak time of lightning impulse for the first strike in MGS, in which we can see the peak air velocity at the vent of the chamber can reach 900 m/s. The strong self-expanding airflow will drive the high temperature thermal plasma in MGS to squirt out to the external space as shown in Fig. 7. Meanwhile, there will be a huge convective heat flux, as shown in Fig. 8.

The chamber at monitoring point F in Fig. 2 is the closest one to the high-voltage electrode in which possess the highest current density compared with other chambers, so the arc in this chamber is more difficult to extinguish.

We can observe in Fig. 9 that the air velocity at point A shows varying degrees of increase in the three lightning impulses and the peak rise reaches the maximum in the first strike. This is mainly because the first strike turns the air in the chamber into hot arc plasma, which results in a temperature rise from 297.15 K to thousands of Kelvin inside the chamber in a very short time. Such a rapid temperature change will generate a great airflow velocity within the chamber. Although at the end of the first strike, the conductivity has almost dropped to 0, the temperature in the chamber has not completely recovered to normal, as shown in Fig. 10, so it is difficult to generate temperature variation at the second strike, therefore, the airflow velocity will not reach that of the first strike even though the amplitude of the second impulse is nearly the same as the first one. So, we can conclude that the airflow velocity is directly proportional to the temperature change rate in MGS.

#### 3.3.2 Impulse arc stage:
A comparison of Figs. 5 and 10 shows that the variation law of velocity and the amplitude of lightning impulse are almost synchronous. In the rising stage of lightning impulse, the high-speed airflow will take away a large amount of joule heat generated by lightning impulse, so the rise of conductivity will be suppressed. When the lightning impulse is in the attenuation stage, the airflow velocity decreases and the convection heat dissipation weakens, hence the conductivity
gradually increases. However, the decrease of joule heat source leads to the insufficient energy supply to the arc plasma, so the conductivity decline rapidly after a brief rise.

3.3.3 Power frequency arc stage: Once the arc channel is formed by the lightning impulse, the power frequency will become a joule heat source providing energy to keep the steady combustion of the arc [23, 24]. It should be noted that the lightning impulse is the premise condition of gap breakdown. However, in the lightning impulse stage, the self-expanding airflow has quickly cut-off the energy channel. Fig. 11 shows the change of joule heat power at the monitoring point F under the three lightning impulses. On the first strike, the joule heat rises rapidly but quickly drops to 0 even though the lightning impulse does not enter the descending edge due to the effect of the self-expanding airflow.

On the other hand, the joule heat power on the subsequent strikes is not of the same order of magnitude as the first one, because on the descending edge of the lightning impulse there is a back-flow in the chamber, as shown in Fig. 12. When the self-expanding airflow is formed inside the chamber, there will be pressure and density difference between the chamber and the outside air, which will lead to the generation of the back-flow. Then the back-flow will react on the arc channel and cut off the supply of joule heat in MGS.

Fig. 13 shows the conductivity changes at the six monitoring points of MGS over half the power-frequency cycle. The results show that on the first strike, conductivity at the monitoring points recovers quickly after rising sharply, which mainly due to the generation of self-expanding airflow extinguishing the arc rapidly. On the second and third strikes, as mentioned above, the temperature has not returned to the normal level and the self-expanding airflow cannot reach the same speed as that of the first
Based on the structure shown in Fig. 2, this study considers the influence of chamber width, chamber depth, the deflection angle, and the number of the chamber on the effect of arc quenching.

4.1 Chamber width and depth

According to the analysis in Section 3.1, the velocity of the self-expanding airflow is directly related to the change rate of temperature.

It can be seen from Fig. 9 that the airflow velocities on the second and third impulses are much lower than that on the first one. This is mainly because the conduction and heat dissipation inside the chambers are blocked in the closed space, so the temperature change rate is much lower than that on the first impulse, as shown in Fig. 8. Increasing the width and decreasing the depth of the chamber within limits can increase the contact area between the arc and the external air.

In this study, Fig. 2 shows the original inner structure of MGS before improvement. The increment in the width of each chamber (denoted as a) and the reduction in the depth of each chamber (denoted as b) are taken as variables for simulation test, and the other conditions are kept unchanged.

Fig. 14 shows the change of airflow velocity of the improved structure at monitoring point F when \( a = 2 \text{ mm} \) and \( b = 3 \text{ mm} \). Compared with Fig. 9, the airflow velocity at the rising peak time of the first impulse is slightly smaller than that before improvement. However, as the heat transfer ability of the chamber enhanced, the airflow velocity in the second and third impulses is significantly increased compared with that before the improvement.

Fig. 15 records the average temperature in the chamber before and after the improvement of chamber depth and width. The results show that the change rate of temperature increases obviously after the improvement. Also, the average temperature in MGS is decreased, which proves the development of arc has been suppressed effectively. Therefore, proper improvement of chamber width and depth is conducive to the generation of high-speed airflow under multiple impulses, hence, enhancing the arc extinguishing ability of MGS.

4.2 Deflection angle

The arc inside MGS will move forward along the direction of the arc extinguishing chamber, and the angle of the arc extinguishing chamber can be changed to affect the direction of the arc movement.

Each chamber consists of two channels between the adjacent electrodes. When the deflection angle (the angle from the X-axis, denoted as r in Figs. 16 and 17) increases, the angle between the direction of electric field force and the direction of charge motion increases, making it difficult for the plasma to flow in the direction of the current.

As is shown in Fig. 16, the wavy line between the two spherical electrodes is the equipotential line of potential distribution. The black arrow line in the vertical direction of the equipotential line indicates the direction of the electric field force received by the plasma at that position. The red arrow line indicates the actual movement direction of the plasma (the direction of the self-expanding flow). Increasing the angle will block the flow direction of the current, thereby the difficulty of arcing increases.

Fig. 17 records the average conductivity in the arc extinguishing chambers at various deflection angles. As we can see, when \( r = 60^\circ \), the average conductivity of the chamber at the first return peak is about 140 S/m. When the angle is reduced to 45°, the average electrical conductivity in the chamber decreases to about 80 S/m. When the angle is reduced to 30°, the average electrical conductivity of the first strike decreases significantly to about only 50 S/m. As can be easily observed through the second and third strikes that the conductivity descends with the reduction of the angle. This phenomenon verifies the corollary of the previous paragraph. The deflection angle of the chamber will affect the deviation angle of the arc plasma formed by stress direction and movement direction. The results show that the smaller the deflection angle, the bigger the deviation angle, the more difficult it would be for the plasma to flow in the direction of the arc.
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is to establish the arc and the lower the average conductivity, which is helpful to extinguish the arc.

Fig. 17 Average conductivity in the arc extinguishing chamber at different deflection angles

Fig. 18 Average current density in the arc extinguishing chamber before and after changing number of chambers

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4.3 Number of chambers
Previous studies have shown that changing a long arc into many short arcs is beneficial to arc extinguishing. In MGS, the chamber has the ability to generate self-expanding airflow to blowout arc, so increasing the number of chambers in the MGS within limits may have a positive impact on arc extinguishing.
In this study, on the basis of a total of four chambers in Fig. 2, the number of chambers is increased to carry out simulation tests. The result in Fig. 18 shows that within a certain range, the larger the number of chambers, the smaller the average current density in the arc extinguishing channel, and the smaller the total current in the arc passage, which is beneficial to arc extinguishing.

5 Conclusion
The arc-extinguishing energy of MGS is the arc itself. Also, in ‘impulse quenching’, the generation of self-expanding airflow comes from the temperature rise and expansion of the conductive fluid in the narrow space. The velocity of the self-expanding airflow is proportional to the rate of the temperature change of the conductive fluid.
When chambers of MGS breakdown by the lightning impulse, the self-expanding airflow is generated at the same time. The strong airflow will take away a large amount of joule heat, which makes the arc difficult to maintain energy from power-frequency through the flashover channel. In this case, the arc is deeply suppressed.
The chamber structure plays a key role in the arc extinguishing effect in MGS. Improving the depth and width of the fracture can increase the conduction heat dissipation of the arc in MGS within limits, which not only improves the cooling rate but also enhances the self-expanding airflow under the following impulses. Decreasing the deflection angle of the arc extinguishing chamber can add the difficulty of arc establishing. Increasing the number of chambers can enhance the effect of arc extinguishing.

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7 References
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