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Cite as: AIP Advances 10, 025326 (2020); https://doi.org/10.1063/1.5129426
Submitted: 28 September 2019 . Accepted: 01 February 2020 . Published Online: 20 February 2020

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Influence of an explosion air shock wave on arc quenching inside a cylinder

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ABSTRACT
To avoid the restriction of the arc energy on the energy quenching of an arc and rapidly quench the arc to restore the insulation characteristics of the gas, the process of arc quenching by an explosion air shock wave is studied in this paper. The interaction between an explosion air shock wave and an arc is considered inside a cylinder structure so that concentrated pressure and airflow velocity can be produced. First, a coupling model of the explosion air shock wave and arc is developed theoretically. Second, according to the model, the explosion air shock wave and arc are simulated by finite element simulation software. It is found that the interaction between the explosion air shock wave and arc is most intense at 0.04 ms, the arc is driven out of the cylinder at 0.087 ms, and then, the arc is gradually quenched. Finally, the test results show that the arc is completely quenched at approximately 0.80 ms, and the value of the peak current is 1 kA. Although there is error between the simulation and test results, the effectiveness of the explosion air shock wave in quenching the arc is still verified, and the arc is quenched over a time scale of milliseconds.

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I. INTRODUCTION
In recent years, the influence of lightning strike accidents on power grid safety has become increasingly prominent, and the short-circuit tripping rate caused by lightning strikes has been very high, accounting for more than 70%. The overvoltage produced by lightning strikes will cause a gas breakdown discharge and form an arc, which will erode the equipment and cause great economic loss.¹ ² Therefore, many countries are studying lightning protection devices that can effectively quench the arc, with the goal of quenching the arc as rapidly as possible and restoring the insulating characteristics of the gas.

The earliest device with an arc quenching capacity was an expulsion-type arrester; in this device, the internal gas-producing pipe generates a large amount of gas fiber in arc quenching due to the high temperature of the arc. Because the growth rate of the gas production lags behind that of the arc energy, there is a mismatch in time and the arc quenching effect is poor, so a metal oxide arrester is widely applied at present.³ In Ref. 4, based on a gas-blown arc motion, an arcing horn was invented; the arc is affected by the release of gas from the organic molecular material in the pipeline, but its arc quenching capability is limited by the influence of the gas production. A long flashover arrester and a multichamber insulator arrester were proposed in Refs. 5 and 6; the principle of these devices is to form a gap and elongate the arc between multiple spherical electrodes. At the same time, the high arc temperature causes the internal gas to expand and form an airflow acting on the arc at the ejector. In Ref. 7, a multifracture arc quenching structure was proposed, employing the physical mechanism where a lightning impulse arc is compressed in the structure to form a multifracture jet flow acting on the arc. However, the arc quenching capability of these lightning protection devices is restricted by the arc energy, so the devices are more commonly used for middle- and low-voltage grades.

Therefore, to avoid the restriction of the arc energy on the energy quenching and achieve a faster and stronger arc quenching
capability, the influence of the pressure and airflow velocity produced by an explosion air shock wave on arc quenching is studied in this paper. An explosion reaction is set in a cylindrical structure to achieve concentrated pressure and velocity. In this paper, the characteristics of the explosion air shock wave inside the cylinder are analyzed theoretically, a physical model of the arc is developed, and the explosion air shock wave and the arc are coupled in the modeling analysis. Second, the arc quenching process is analyzed by finite element simulation software, and the optimal arc quenching action is studied. Finally, the effectiveness of the explosion air shock wave in quenching the arc is verified by a test, and the cause of the error between the simulation and test results is analyzed. These findings provide a reference for the study of the coupling effect of the blast air shock wave and arc in future theories, simulations, and tests.

II. CHARACTERISTICS OF AN EXPLOSION AIR SHOCK WAVE

A shock wave is reflected many times due to the constraint of a cylinder wall and forms a multwave superposition, and the resulting flow field is much more complex than a free field. To analyze a shock affected by the reflection of a wall, a mirror explosion center is introduced. As an example, point T at the outlet is shown in Fig. 1, where S is the center of the explosion and S1 and S2 are the symmetrical mirror explosion centers of S on the upper and lower walls, respectively. The shock wave produced by S is reflected by the wall at points T1 and T2 and acts on point T. Paths 2 and 3 are equivalent to the path, where S1 and S2 act directly on point T. The explosion shock wave produced by the explosion center S acts directly on point T through path 1, which is superimposed with paths 2 and 3 to form the total shock wave load at point T.

The explosion load of any point inside the cylinder is a combination of the direct and reflective actions of the explosion shock wave, which is mainly manifested in an increase in the pressure and airflow velocity. Due to the existence of the multwave superposition, there are multiple pressure and velocity peaks.

The explosion material explodes in air and forms high-temperature and high-pressure products in an instant. The explosive products are continuously expanded to compress the air and form a shock wave. The pressure of trinitrotoluene (TNT) explosive products is described by the Jones–Wilkins–Lee equation of state (JWL EOS),

\[
P = A\left(1 - \frac{\omega}{R_1V}\right)e^{-\frac{R_1}{V}} + B\left(1 - \frac{\omega}{R_2V}\right)e^{-\frac{R_2}{V}} + \frac{\omega E_1}{V},
\]

where \(P, V,\) and \(E_1\) denote the pressure, specific volume, and unit volumetric internal energy of the explosive products, respectively, and \(A, B, R_1, R_2,\) and \(\omega\) are constant. The first term on the right of the equation is the high-pressure section, the second term is the medium-pressure section, and the third term represents the low-pressure section.

The mutual relation in the JWL EOS is derived from the Chapman–Jouguet (CJ) condition and the Hugoniot expression, where the specific volume and pressure under the CJ condition can be expressed as follows:

\[
V_{\text{CJ}} = \frac{y}{y + 1}, \quad P_{\text{CJ}} = \frac{\rho_0D^2}{y + 1},
\]

where \(V_{\text{CJ}}\) and \(P_{\text{CJ}}\) are the specific volume and pressure under the CJ condition, respectively, \(\rho_0\) is the initial density of the explosive, \(D\) is the explosion velocity, and \(y\) is the multisquare index of the explosion products.

The air is described by a linear equation of state as follows:

\[
P = C_0 + C_1m + C_2m^2 + C_3m^3 + (C_4 + C_5m + C_6m^2)E_2,
\]

where \(P\) is the air pressure, \(m\) is the relative volume, and \(E_2\) is the internal energy of the unit volume.

III. COUPLING MODELING OF THE EXPLOSION AIR SHOCK WAVE AND THE ARC

A. Arc physical model

Assuming that the arc is in a high-pressure state (the pressure value is higher than 0.1 MPa), in which it is electrically neutral and achieves local thermodynamic equilibrium, all particles can reach the same temperature. At the same time, it is assumed that the law of continuum mechanics is applicable to the arc plasma, satisfying mass conservation, momentum conservation, and energy conservation.

The law of mass conservation is

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]
where \( \rho \) is the density and \( \mathbf{v} \) is the velocity vector. This law indicates that the quality of the arc plasma remains unchanged in the system.

The law of conservation of momentum is

\[
\rho \frac{\partial \mathbf{v}}{\partial t} = \nabla P_a + \mathbf{f}_i,
\]

(5)

where \( P_a \) is the pressure of arc plasma, \( \mathbf{f}_i \) denotes the vector of the force, and the summation represents the resultant force. The equation is a simplified form of the Navier–Stokes equation, which shows that the rate of change of the velocity vector (acceleration) is proportional to the pressure gradient and resultant force.

The law of conservation of energy is

\[
\rho \frac{\partial h}{\partial t} = \nabla \cdot \left( \frac{\mathbf{q}}{A_i} \right) - w_r + w_i + w_f,
\]

(6)

where \( w_r \) is the radiation energy density, \( w_i \) is the consumed energy density from internal friction work, \( w_f \) is the thermal density generated by the heat source in the arc, \( h \) is the specific enthalpy, \( \mathbf{q} \) is the heat flux vector, and \( A_i \) is the arc cross-sectional area. This law indicates that the total energy remains the same in the arc plasma system.

Consider that the equation of state for a gas is

\[
P_0 = \frac{\rho}{M} RT,
\]

(7)

where \( P_0 \) is the gas pressure; \( T \) is the gas temperature; \( R \) is the universal gas constant, which has a value of 8.314 J/mol \( \cdot \) K; and \( M \) is the molar mass. This equation is the equation of state for an ideal gas.

The relationship between the state variables, such as temperature, pressure, volume, and internal energy, is determined by the equation of state for the gas. Physics and thermodynamics are involved in the study of arc physical modeling. It is also necessary to introduce the generalized Ohm’s law and Maxwell’s equations in the process of solving the arc physical model.

The generalized Ohm’s law is

\[
\mathbf{J} = \sigma (\mathbf{v} + \mathbf{v} \times \mathbf{B}),
\]

(8)

where \( \mathbf{J} \) is the current density vector, \( \sigma \) is the conductivity, \( \mathbf{B} \) is the magnetic induction intensity vector, and \( \mathbf{E} \) is the electric field strength vector.

Maxwell’s equation in differential form is

\[
\begin{align*}
\nabla \cdot \mathbf{E} &= \frac{\lambda}{\varepsilon_0} \rho_d, \\
\nabla \cdot \mathbf{B} &= 0, \\
\n\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\
\n\nabla \times \mathbf{B} &= \mu_0 \left( \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \right),
\end{align*}
\]

(9)

where \( \varepsilon_0 \) is the vacuum dielectric constant, which has a value of 8.854 \( \times 10^{-12} \) F/m; \( \mu_0 \) is the vacuum magnetic permeability, which has a value of \( 4\pi \times 10^{-7} \) H/m; and \( \rho_d \) is the charge density.

**B. Coupling modeling**

The process of an explosion air shock wave acting on an arc is essentially a coupling process between the electromagnetic field and the fluid field. According to the arc modeling assumption, the whole system achieves local thermodynamic equilibrium, and the arc plasma is regarded as a Newton fluid ignoring thermal radiation and viscous dissipation. At the same time, changes in the space charge, displacement current, and electromagnetic field with time are not taken into account; the modeling focuses on the action of the electromagnetic force, so the system can be approximated as a three-dimensional viscous compressible magnetic fluid field based on the Navier–Stokes equations.

The control equations are obtained by modifying and simplifying the arc physical modeling equation. The resultant force term in the law of conservation of momentum can be considered as the sum of the divergence of the stresses and the electromagnetic force, so the resultant force term in formula (5) can be expressed as follows:

\[
\sum f_i = \nabla \cdot (\tau_{ij} \cdot \mathbf{e}_i) + F_i,
\]

(10)

where \( \tau_{ij} \) denotes the stress in different directions, which is related to the dynamic viscosity coefficient, and \( F_i \) denotes the electromagnetic force in different directions, \( F_i = (\mathbf{J} \times \mathbf{B})_i \).

\[
\begin{align*}
\tau_{ij} &= \lambda (\nabla \cdot \mathbf{v}) \delta_{ij} + 2 \mu \frac{\partial \mathbf{v}_i}{\partial t} + \mu \left( \frac{\partial \mathbf{v}_i}{\partial r_i} + \frac{\partial \mathbf{v}_j}{\partial r_j} \right), \\
\end{align*}
\]

(11)

where \( \mu \) is the first dynamic viscosity coefficient, \( \lambda \) is the second dynamic viscosity coefficient, and \( r_i \) is the distance to the center of the arc in the different directions, \( i = x, y, z \).

The radiation energy density in formula (6) is given by an empirical formula as follows:

\[
w_r = 4ab(T^4 - T_0^4),
\]

(12)

where \( a \) and \( b \) are constant and \( T \) and \( T_0 \) denote the internal temperature of the arc and the initial ambient temperature, respectively.

The thermal density produced by the heat source in the arc is mainly the Joule heat caused by the current, so the thermal density in formula (6) is as follows:

\[
w_i = J^2 / \sigma.
\]

(13)

The consumed energy density of the internal friction force in the arc is mainly the partial derivative of the pressure with respect to time, so in formula (6), the consumed energy density is represented as follows:

\[
w_i = \partial p / \partial t.
\]

(14)

If only the action of the electromagnetic force is taken into account during the arc quenching process and the changes in the space charge, induction electric field, and electromagnetic field with time are ignored, Maxwell’s equations in the arc physical model can be simplified as follows:
The JWL EOS parameters of the TNT explosive products are performed. The initial density is set to 15.8 kg/m$^3$.

A specific shape and strength, and a fluid-solid coupling simulation arc, is used to simulate the arc. The arc is equivalent to a fluid with DYN, the weak energy material of TNT-flash, which is similar to the equation (3).

And the other parameters are shown in Table II according to formula (1). The initial air density is 1.225 kg/m$^3$, the initial pressure in the air is 1 atm (0.1 MPa), and the CJ specific energy is 50 J/m$^3$. The JWL EOS parameters of the TNT explosive products are shown in Table I according to formula (1). The initial air density is 1.225 kg/m$^3$, the initial pressure in the air is 1 atm (0.1 MPa), and the thermal conductivity is 1.4, the initial temperature is 296 K, and the CJ specific energy is 50 J/m$^3$. The JWL EOS parameters of the TNT explosive products are shown in Table I according to formula (1).

### TABLE I. JWL EOS parameters of TNT explosion products.

| A (kPa)   | B (kPa)   | R$_1$ | R$_2$ | $\omega$ | $D$ (m/s) | $E_1$ (J/m$^3$) | $P_{CJ}$ (kPa) |
|-----------|-----------|-------|-------|----------|-----------|----------------|----------------|
| $3.712 \times 10^8$ | $3.231 \times 10^8$ | 4.15  | 0.95  | 0.3      | 6930      | $7.0 \times 10^9$ | $2.1 \times 10^7$ |

By studying the characteristics of the explosion air shock wave and the modeling of the arc, it can be found that the point of penetration is the equation of state. Therefore, the coupling of the airflow field formed by the explosion air shock wave and the electromagnetic field formed by the arc is considered by the equation of state, and the appropriate assumptions are valid.

### IV. SIMULATION ANALYSIS OF THE EXPLOSION SHOCK WAVE IN ARC QUENCHING

#### A. Simulation modeling

The simulation model of the explosion air shock wave in the arc quenching process involves nonlinear dynamic coupling between the gas and electromagnetic fluid. In this paper, ANSYS AUTO-DAY finite element software is used to simulate the explosion shock wave. The shock wavefront pressure is assumed to be zero, and the chemical reaction of the explosive is complete, which means that all energy generated by the explosion contributes to the shock wave propagation.

The main elements of the simulation model include the cylinder, the air, the TNT explosive, and the arc. The cylinder length is 20 cm, the outer diameter is 7 cm, and the inner diameter is 6 cm. The mass of the solid TNT explosive charge is $2 \times 10^4$ mg, $4 \times 10^4$ mg, and $6 \times 10^4$ mg, and the density is $1.58 \times 10^3$ kg/m$^3$.

The JWL EOS parameters of the TNT explosive products are shown in Table I according to formula (1). The initial air density is 1.225 kg/m$^3$, the initial pressure in the air is 1 atm (0.1 MPa), the thermal conductivity is 1.4, the initial temperature is 296 K, and the other parameters are shown in Table II according to formula (3).

Because the modeling of the arc cannot be realized in AUTO-DYN, the weak energy material of TNT-flash, which is similar to the arc, is used to simulate the arc. The arc is equivalent to a fluid with a specific shape and strength, and a fluid-solid coupling simulation is performed. The initial density is set to 15.8 kg/m$^3$, the initial specific energy is $50$ J/m$^3$, the CJ pressure is $2.4 \times 10^7$ kPa, and the CJ explosion velocity is $2.4 \times 10^7$ m/s.

### TABLE II. Parameters of air.

| $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $E_2$ (J/m$^3$) |
|-------|-------|-------|-------|-------|-------|-------|----------------|
| −0.1  | 0     | 0     | 0     | 0.4   | 0.4   | 0     | $2.5 \times 10^6$ |

The geometric model is established, as shown in Fig. 2, where the green part is set to TNT, the cylinder is a rigid body, the red part in the cylinder is a TNT-flash class arc material, and the remainder is air. Five Gaussian integral points are employed for the observation: point 1 and point 5 are located at the inlet and the outlet, respectively, of the cylinder wall, respectively, and point 2, point 3, and point 4 coincide with the inlet, middle, and outlet, respectively, of the cylinder along the direction of the cylinder axis. Then, the model is meshed, and the calculations are performed. The air domain and TNT-flash define each other’s connection with the cylinder and TNT via fluid-solid coupling. The outer part of the cylinder is fully constrained.

#### B. Simulation result analysis

When the explosion air shock wave couples with the arc plasma, the generated high-velocity airflow increases the pressure in the cylinder and accelerates the movement of particles in the arc. The free travel of particles is reduced, and the deionization of the arc plasma is accelerated. The arc temperature and conductivity decrease. The dissipation of energy finally results in arc quenching.

The pressure and velocity of the point 2 Gaussian integral for different solid-state TNT explosive charge masses vary with time, as shown in Figs. 3 and 4, respectively.

The pressure and velocity of the point 2 Gaussian integral for different solid-state TNT explosive charge masses vary with time, as shown in Figs. 3 and 4, respectively.

The increase in the charge mass causes an increase in the amount of explosives involved in the reaction, and the energy released by the explosion reaction increases, which causes an increase in pressure and velocity. Because the charge mass and the duration of the explosion chemical reaction increase, the formation of the air shock wave has a large amount of function, which causes the start time of the strong pressure action to lag and the duration of the action to increase, as shown in Fig. 3.

When the charge mass increases to a certain extent, the shock wave velocity slowly increases, as shown in Fig. 4, which indicates...
FIG. 3. Pressure of different charge mass.

FIG. 4. Z-Velocity of different charge mass.

FIG. 5. Temporal variation in pressure.

FIG. 6. Temporal variation in the z-velocity.

that the velocity is not linearly changed with the charge mass. Because the amount of charge increases to a certain extent and extra energy must be consumed to break the agglomerated mixed explosive, the explosion energy loss increases, which causes a slow growth in the velocity. Therefore, the determination of charge mass needs to take into account multiple factors, such as pressure start time, pressure duration, and shock wave velocity. In this paper, a $4 \times 10^4$ mg charge mass is mainly used for follow-up study.
The explosion air shock wave is the dominant factor in arc quenching. The curves of the temporal variation in the pressure and velocity vector for the $4 \times 10^4$ mg charge mass at the five Gaussian integral points are simulated and analyzed, and pressure nephograms for different times are obtained.

Figure 5 shows the curves of the temporal variation in the pressure at each Gaussian point after the explosion air shock wave couples to the arc. From the curves, the earliest peak pressure occurs at points 2 and 1, and the corresponding times are 0.008 ms and 0.012 ms, respectively. Because point 1 is close to the cylinder wall and is affected by the superposition of the reflections of the wall, the value of the first pressure peak of point 1 is approximately $4 \times 10^5$ kPa. Because the air shock wave is reflected by the cylinder and propagates in the cylinder axial direction, the value of the second pressure peak at point 1 is obviously lower than the value of the first pressure peak, while the value of the second pressure peak at point 2 is greater than the value of the first pressure peak. The peak pressure at the other points is approximately steady and maintains a low value.

Figure 6 shows the curves of the temporal variation in the z-axis velocity at each Gaussian point. From the curves, the high-velocity airflow is first generated at points one and two, and after approximately 0.06 ms, the airflow velocity is generated at point five. Because the propagation process of the explosion air shock wave requires time and point five is at the outlet of the cylinder, the airflow velocity peak at point five obviously lags behind that at points one and two. Two velocity peaks appear at point two, and the first velocity peak (approximately 2500 m/s) is higher than the second velocity peak (~1500 m/s) due to the energy dissipation associated with the coupling of the explosion air shock wave and the arc.

By comparing Figs. 5 and 6, the time of the second velocity peak and the second pressure peak is approximately 0.04 ms, which indicates that this time is associated with the most intense explosion air shock wave that acts on the arc. The value of the velocity at approximately 0.08 ms falls below 500 m/s, indicating that the coupling influence has substantially abated and the arc is quenched at this time.
FIG. 8. Test circuit. G: generator; DS: insulation switch; PS: protection switch; T: short-circuit test transformer; L: limiting reactor; CM: current measurement; VM: voltage measurement; MS: make switch; TO: test object; MF: metal fuse; and C: camera.

FIG. 9. Process of the explosion air shock wave quenching the arc, as recorded by the camera.
which time the medium between the two electrodes is converted to a conductor to an insulator; that is, the arc is completely quenched. The test results also show that the energy dissipation of the arc is accelerated because of the action of the explosive air shock wave, which is beneficial for the deionization of the arc plasma, so the arc is quenched over a time scale of milliseconds.

There is error between the simulation and test results, and the main reasons for this error are as follows:

1. In the simulation, the special weak energy material TNTFlash is used to simulate the arc without an external energy injection. While the test arc is generated by the power-frequency energy in the test, the simulated time associated with the arc being driven out of the cylinder is shorter than that in the test results.
2. The arc adopts a fluid of a specific shape and intensity in the simulation, its spatial distribution is regular, and the force is relatively concentrated. However, the shape of the power-frequency arc in the test is irregular and the physical shapes of the arc root and the arc column are different, which affects the arc quenching.
3. The ideal state is adopted without considering the influence of an arc rebreakdown in the simulation, while the actual air state in the test cannot be ignored. In the test, due to the thermal buoyancy and the resistance caused by the external gap, there is also a possibility of a breakdown in the arc quenching process, which will also affect the arc quenching time.

VI. CONCLUSION

1. The propagation characteristics of the explosion air shock wave inside the cylinder have an influence on the arc quenching. The superposition of the reflections of the air shock wave inside the cylinder generates high-velocity airflow acting on the arc plasma such that the deionization of the arc is enhanced and the energy dissipation is accelerated.
2. According to the simulation analysis, the most intense shock wave acts on the arc at approximately 0.04 ms, and then, the arc is completely quenched at approximately 0.08 ms. However, special materials and ideal conditions are used in the simulation process, so there is error between the simulation and actual test results. It is necessary to improve the optimization of the simulation in future research.
3. According to the test analysis, it is concluded that the explosion air shock wave begins to act on the arc at approximately 0.04 ms, the arc is completely quenched at approximately 0.08 ms, and the value of the current peak of the arc is 1 kA. Although the actual test time is longer than the corresponding time in the simulation, the arc is completely quenched by the explosive air shock wave over a time scale of microseconds.

ACKNOWLEDGMENTS

This work was supported by the Special Project of Guangxi innovation-driven development (AA18242050) and the Key R & D Project in Guangxi (AB18126095). The authors would like to thank all the researchers in Power Transmission Lightning Protection Engineering Technology Research Center of Guangxi.
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