Arc Parameters around Current Zero in CO₂-Blast Quenching Chamber and their Dependences on Filled Pressure

Yasunobu Yokomizu Senior Member (Nagoya University, Japan)
Ikuma Morooka Student Member (Nagoya University, Japan)
Toshiro Matsumura Member (Nagoya University, Japan)

Keywords: circuit breaker, CO₂, arc time constant, arc power loss

From the viewpoint of the environmental issues, SF₆ gas circuit breakers are expected to adopt an environmentally benign gas as the arc quenching gas. At the present stage, the CO₂ is expected to be promising quenching gas, especially for high-voltage circuit breakers. However, the arc interrupting process in CO₂ is not yet fully understood.

For an AC high-voltage circuit breaker, arc parameters—an arc time constant and an arc power loss—around a current-zero are known to be important factors for the interrupting process of an AC arc. Thus, the present study was undertaken to measure the arc parameters of the CO₂ arc before a current-zero during current-interruption process in a CO₂-blast quenching chamber. This study was also aimed at finding out the arc parameters for different CO₂ pressures in the range of 0.1 and 0.2 MPa. Finally, theoretical calculations are performed so that the arc parameters on the pressure is interpreted on the basis of physical aspects of the interrupting arc.

The arc parameters were determined from an arc conductance measured before a current zero, on the basis of the expression proposed by Mayr. Figure 1 shows the arc power loss during the time period from −20 to −2 μs for the pressure of 0.1 and 0.2 MPa, while Fig. 2 presents the arc time constant. The CO₂ arc at the pressure of 0.1 MPa proved from Fig. 1 to show a decrease in the arc power loss from about 5 to 1.4 kW with the passage of the time from −20 to −2 μs and is found from Fig. 2 to reveal a decline in the arc time constant from about 5 to 1.5 μs with the same elapse of the time. Figures 1 and 2 also represents that the increase in the pressure to 0.2 MPa causes a growth in the arc power loss, but resulting no marked change in the time constant.

To interpret these phenomena, theoretical calculations were carried out to obtain the arc power loss \( q \) and the arc time constant \( \theta \) for different pressures. The CO₂ pressure was intentionally set to be in a wide range from 0.1 to 0.5 MPa in order to obtain the dependences of \( q \) and \( \theta \) on the pressure over this wide range. We researched a wall-stabilized arc to obtain an arc aspect under a transient state, because this arc gives us a lot of fundamental properties. The theoretical calculation revealed that the CO₂ arc before the current zero loses the higher power at higher pressure and that the CO₂ arc has the time constant independent of the pressure over the range from 0.1 to 0.5 MPa.

The phenomena derived from theoretical calculations were interpreted in terms of fundamental properties such as thermodynamic properties. As a result, above dependences of the arc power loss on the pressure proved to result from augment in the enthalpy with the pressure. In addition, the independence of the time constant on the pressure was explained in terms of a conducting radius and a thermal diffusivity.

Fig. 1. Arc power loss of CO₂ arc toward current zero for pressures of 0.1 and 0.2 MPa

Fig. 2. Arc time constant of CO₂ arc toward current zero for pressures of 0.1 and 0.2 MPa
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Yasunobu Yokomizu∗ Senior Member
Ikuma Morooka∗ Student Member
Toshiro Matsumura∗ Member

The arc power-loss and the arc time-constant of a CO₂ arc before the current zero during a current-interruption process were measured in a CO₂-blast quenching chamber. The CO₂ arc at a pressure of 0.1 MPa showed decrease in the arc power loss from about 5 to 1.4 kW with the passage of a time from −20 to −2 µs and revealed decline in the arc time constant from about 5 to 1.5 µs with the same elapse of the time. The increase in the pressure to 0.2 MPa caused growth in the arc power loss, but resulting in no significant variation in the time constant. These dependences of the arc parameters on the pressure were explained on the basis of theoretical calculation on an extinguishing arc.

Keywords: circuit breaker, CO₂, arc time constant, arc power loss

1. Introduction

Sulfur hexafluoride (SF₆) is widely used as an arc-quenching gas in a gas circuit breaker. Nevertheless, the SF₆ has a global warming potential of as high as 23900. From the viewpoint of the environmental issues, the circuit breaker is expected to adopt the gas not having greenhouse effect as the quenching medium.

It is well known that the difference in the quenching gas influences arc properties, and thus current interrupting performance. Until now, we have investigated the arc properties and the interrupting performance for various gases (1) (3). These investigations lead us to the results that CO₂ is a candidate as an alternative quenching gas to SF₆. Although having global warming effect, CO₂ has very much lower global-warming-potential than SF₆. Other attempts have been also made to show that the CO₂ is a candidate as an alternative quenching gas to SF₆ (4) (5).

For an ac circuit breaker, the decaying behavior of the arc conductance around a current-zero is known to be an important factor for the interrupting process of an ac arc. In most cases, the decaying behavior of the arc conductance is discussed in terms of arc parameters: an arc time constant and an arc power loss. However, there has been research work on the arc parameters of the CO₂ arc.

The first purpose of the present research is to measure the arc parameters of the CO₂ arc before a current-zero in a current-interruption process. The second aim is to find out the arc parameters for different CO₂ pressures. Thus, the CO₂ pressure filled in an arc quenching chamber is varied to be 0.1 and 0.2 MPa. Finally, theoretical calculation is performed so that dependences of the arc parameters on the pressure is interpreted on the basis of physical aspects of the interrupting arc.

∗ Department of Electrical Engineering and Computer Science, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan

2. Measurement Method of Arc Parameters in CO₂

2.1 Arc Quenching Chamber

The arc sustained in CO₂ flow was established in an arc quenching chamber of a double-pressure type interrupting apparatus. Figure 1 illustrates the longitudinal cross section of an inner space of the arc-quenching chamber. Both a stationary contact and a moving one are made of copper-tungsten alloy. The CO₂ flows upward through a nozzle to blow an arc. A nozzle is made of PTFE. The inner diameter of the nozzle throat is 10 mm.

The CO₂ was filled at pressures of 0.1 and 0.2 MPa in the arc-quenching chamber to estimate the dependence of the arc parameters on the pressure in the arc-quenching chamber. The interrupting apparatus used in the experiment has not only the arc-quenching chamber but also a high-pressure storage tank. In this type, the high-pressure storage tank has CO₂ at a higher pressure than the arc-quenching chamber, and thus this difference in the pressure produces the gas blast through the nozzle in the arc-quenching chamber to disappear.
an arc energy principally through the convection mechanism of the gas blast. The storage pressure of the CO₂ in the tank was adjusted to be 0.35 MPa for the case of the arc-chamber pressure of 0.1 MPa so that the CO₂ flow rate was set to be about 1,500 liters/min. To achieve the same flow rate for the case of the arc-chamber pressure of 0.2 MPa, the CO₂ was filled at a pressure of 0.70 MPa in the storage tank. This is because an another calculation result revealed that the CO₂ flow rate Q is expressed by Q = k(P_{tank} − P_{cha})/P_{cha}, where P_{tank}: the pressure in the storage tank, P_{cha}: the pressure in the arc chamber, k: a constant determined from various factors such as the volume of the storage tank.

2.2 Measurement of Arc Conductance

Using a 3580 µF capacitor bank and a 3.7 mH reactor, a sinusoidal damping current with a frequency of 43.5 Hz was generated. The current was supplied to the damping current with a frequency of 43.5 Hz was generated. Measuring i were measured. Measuring θ and η were measured. Measuring Q flow rate was measured. Measuring an arc energy principally through the convection mechanism was measured.

The time variations of an arc voltage v and an arc current i were measured. Measuring v and i allowed to determine a power p = vi inputted to the arc and an arc conductance q = i/v at particular times around the second current-zero. Furthermore, from the conductance g, a quantity η = (dq/dt)/g was also determined. The input power p and the quantity η are required to evaluate the arc parameters.

2.3 Process of Determining Arc Parameters

The arc conductance g is assumed to vary with a passage of time t around current-zero, in accordance with

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{\theta} \left( \frac{p}{q} - 1 \right)
\]

where θ is an arc time constant and q is an arc power loss. The quantities, θ and g, are called arc parameters. The Eq. (1) has been given by Mayr\(^\text{m}\). According to this expression, q and θ at a certain time t₀ are determined from measured p(= vi) and η(= (dq/dt)/g) in the procedures mentioned below.

(i) The Eq. (1) indicates that η is expressed as a function of the input power p. Thus, η measured at particular times are plotted against the input power p on a graph.

(ii) The procedure (i) allows us to obtain the form of a function of η = f(p) around a certain time t₀. From the function, the tangent of the function is obtained at the time t₀:

\[
\eta = f'(p|_{t=t₀})(p - p|_{t=t₀}) + \eta|_{t=t₀}, \quad \cdots \cdots \cdots (2)
\]

(iii) Substituting 0 for p in Eq. (2) allows evaluation of the quantity η at p = 0. This evaluated η corresponds to 1/θ at the time t₀:

\[
\eta|_{t=t₀} = \frac{1}{\theta} \left( p|_{t=t₀} - \eta|_{t=t₀} \right), \quad \cdots \cdots \cdots (3)
\]

(iv) Substituting 0 for p in Eq. (2) allows evaluation of the quantity η at p = 0. This evaluated η corresponds to 1/θ at the time t₀:

\[
\eta|_{t=t₀} = \frac{1}{\theta} \left( p|_{t=t₀} - \eta|_{t=t₀} \right), \quad \cdots \cdots \cdots (4)
\]

3. Arc Parameters for Different CO₂ Pressures

3.1 Examples of Waveforms

Figure 2 shows an example of whole waveforms of the arc current i, the arc voltage v and the distance between contacts. These waveforms were obtained for a pressure of 0.1 MPa in the arc-quenching chamber and the second peak of interrupted current, I_{peak}, of 2.1 kA.

Figure 3(a) depicts the waveforms of the current i and the arc voltage v during the time period from −20 to −2 µs before the second-current-zero. The time of zero corresponds to the time at which the instantaneous current is zero. This figure also show the conductance g derived from i and v. Figure 3(b) shows the value of (dg/dt)/g plotted against the input power.
3.2 Arc Power Loss Figure 4 indicates the arc power loss \( q \) during the time period from \(-20 \) to \(-2 \) \( \mu s \) for the arc-chamber pressures of 0.1 and 0.2 MPa. The CO\(_2\) arc for 0.1 MPa is found from Fig. 4 to have \( q \) of 3–6 kW around \(-20 \) \( \mu s \) and to show decrease in \( q \) to 0.7–2 kW with the elapse of time to \(-2 \) \( \mu s \). As also seen in Fig. 4, the CO\(_2\) arc for 0.2 MPa also shows reduction in \( q \) with the same elapse of the time. However, the CO\(_2\) arc has higher \( q \) for 0.2 MPa than for 0.1 MPa during \(-20 \) to \(-2 \) \( \mu s \).

3.3 Arc Time Constant Figure 5 presents the arc time constant during the time of \(-20 \) to \(-2 \) \( \mu s \) around the current zero. The open circles correspond to the case for the pressure of 0.1 MPa. The CO\(_2\) arc for 0.1 MPa have the time constant \( \theta \) of 4–7 \( \mu s \) to present a decrease in \( \theta \) to 1–2 \( \mu s \) with the passage of the time to \(-2 \) \( \mu s \). While, in Fig. 5, open triangles designate \( \theta \) for 0.2 MPa. The CO\(_2\) arc for 0.2 MPa has \( \theta \) almost same as that for 0.1 MPa.

3.4 Discussion As seen in Figs. 4 and 5, the arc power loss \( q \) and the arc time constant \( \theta \) vary with the elapsed time. However the time variations in \( q \) and \( \theta \) presumably result from the time evaluation in a physical condition of the arc. On the basis of these two considerations, \( q \) and \( \theta \) highly seem to depend on the arc physical condition. We considered that the representative of the arc condition was the arc conductance. Therefore evaluated \( q \) and \( \theta \) will be plotted against the measured \( g \), as stated below. Further \( q \) and \( \theta \) will be expressed in terms of \( g \). These deviations of \( q \) and \( \theta \) as a function of \( g \) are frequently carried out in research field of the arc interruption, because obtaining these functions enables us to make numerical calculations such as the prediction of the current interruption performance(7).

In Fig. 6(a), open circles denote \( q \) plotted against the conductance \( g \) for the pressure of 0.1 MPa, while, in Fig. 6(b) open circles designate \( \theta \) plotted against \( g \) for the pressure of 0.1 MPa. From Figs. 6(a) and (b), \( q \) and \( \theta \) exhibit almost straight variation with \( g \) on a graph of log-log plots. These facts suggest that \( q \) and \( \theta \) can be approximated in the forms

\[
q = a_1 g^{\xi_1} \quad \text{and} \quad \theta = b_1 g^{\eta_1}
\]

respectively, where \( a_1, \xi_1, b_1 \) and \( \eta_1 \) are constants determined from the measured values. The least square method enabled us to obtain approximated \( q \) [W] and \( \theta \) [s] as a function of \( g \) [S] for 0.1 MPa. The broken
lines shown in Figs. 6(a) and (b) represent the approximated curves.

In the same way as above, \( q \) was also expressed in terms of \( g \) for 0.2 MPa. In Fig. 6(a), filled line shows the approximated \( g \). The loss \( q \) in terms of \( g \) for 0.1 and 0.2 MPa are written in Fig. 6(a). For 0.1 MPa, the arc power loss \( q \) is found from the expression to be 7.0 kW for 100 mS and to decline with 0.545 of \( g \). The power loss \( q \) for 0.2 MPa also diminishes with \( g \) at the almost same exponent, but being 1.7 times as high as that for 0.1 MPa.

Furthermore, in the same way as above, \( \theta \) for 0.2 MPa was also approximated in terms of \( g \) and the derived expressions are written in Fig. 6(b). The arc time constant for 0.1 MPa is 8.6 \( \mu \)s at 100 mS and abates with 0.620 of \( g \). This arc time constant for 0.1 MPa is almost as large as that for 0.2 MPa.

4. Interpretation of Dependences of Arc Parameters on Pressure

4.1 Purpose The experimental result revealed that the rise in \( CO_2 \) pressure from 0.1 to 0.2 MPa augmented the arc power loss around the current zero, while no longer changing the arc time constant. To interpret these phenomena, a theoretical calculation was carried out to obtain the loss \( q \) and the arc time constant \( \theta \) for different pressures. We researched a wall-stabilized arc to obtain an arc axis under a transient state, because this arc gives us a lot of fundamental properties. In this calculation, \( CO_2 \) was flowed along an arc-axis direction in the space enclosed with the wall to loss the arc energy through the convection mechanism. This is because the \( CO_2 \) blast was performed in the above-mentioned experiment and thus the arc energy in the experiment principally dissapears through the convection mechanism.

4.2 Calculation Method

4.2.1 Equations for deriving transient conductance

On the assumption that local thermal equilibrium is established in the arc and that the arc has an axis-symmetry distribution of a temperature, an energy balance equation expressing the arc sustained in an axial gas flow under a transient state has been found to be written in the following form:

\[
\frac{\partial \rho}{\partial t} + \nabla \mathbf{V}_i \cdot \nabla \rho = \int_{0}^{R} 2\pi r \rho \sigma \frac{\partial T}{\partial r} \, dr + \int_{0}^{R} 2\pi r \rho \sigma \frac{\partial T}{\partial r} \, dr
\]

where \( i \) current, \( \rho \) mass density, \( V_i \) flow velocity at the center of the arc cross-section, \( \kappa \) thermal conductivity and \( h \) enthalpy at 300 K. This expression (5) has been confirmed to be valid for a transient arc sustained in the axial direction. The third term in the Eq. (5) expresses a convection loss resulting from the quenching gas flow in the axial direction.

In addition to the Eq. (5), a mass conservation equation is given by

\[
\frac{\partial \rho}{\partial t} + \nabla \mathbf{V}_i \cdot \nabla \rho = \frac{\partial}{\partial r} \left( \rho \frac{\partial \mathbf{V}_i}{\partial r} \right)
\]

While, the conductance \( g \) is expressed in terms of \( \sigma \) or in terms of an arc voltage \( E \) per unit length:

\[
g = \frac{2\pi \rho \sigma}{E} \int_{0}^{R} \frac{dr}{dr} \left( \frac{\partial \mathbf{V}_i}{\partial r} \right) \frac{\partial T}{\partial r} \, dr
\]

4.2.2 Equations for deriving arc power and time constant

Solving the Eqs. (5)–(7) under the calculation conditions mentioned later leads to the time variation in \( g \) and \( T \) around the current zero. From the derived \( T \) and \( g \), the arc power loss \( q \) and the arc time constant \( \theta \) are calculated:

\[
q = \frac{\partial \rho}{\partial t} + \nabla \mathbf{V}_i \cdot \nabla \rho \sigma \frac{\partial T}{\partial r} \, dr + \int_{0}^{R} \frac{dr}{dr} \left( \frac{\partial \mathbf{V}_i}{\partial r} \right) \frac{\partial T}{\partial r} \, dr
\]

In solving the Eq. (5)–(9), we intentionally set the \( CO_2 \) pressure to be in a wide range of 0.1 to 0.5 MPa in order to find out the dependences of \( q \) and \( \theta \) on the pressure over the wide range. Hence the thermodynamic and the transport properties of the high-temperature \( CO_2 \) for 0.1–0.5 MPa were used.

In accordance with Eq. (8), the arc power loss \( q^{(1)} \), \( q^{(2)} \), \( q^{(3)} \) and \( q^{(5)} \) were obtained for the pressures of 0.1, 0.2, 0.3 and 0.5 MPa, respectively. Further, in accordance with Eq. (9), the arc time constant \( \theta^{(1)} \), \( \theta^{(2)} \), \( \theta^{(3)} \) and \( \theta^{(5)} \) were obtained for the pressures of 0.1, 0.2, 0.3 and 0.5 MPa, respectively.

An interrupting current \( i \) before a current zero was assumed to decrease from 50 to 0 A at a slope \( di/dt \) of 0.3 A/\( \mu \)s, after the arc in a steady state burned at a current of 50 A. In the present calculation, \( R \) and \( l_{arc} \) were set to be equal to 5 mm and 15 mm, respectively. Furthermore \( V_i \) was set to be 26 m/s, corresponding to a gas flow rate of 100 liters/min. Strictly speaking, \( di/dt \) and the flow rate are lower than those under the experimental conditions. However we focused on explaining theoretically that the augment in the pressure raises the arc power, while causing no change in the arc time constant, on the basis of the arc physics such as the radial distribution of the temperature and the thermodynamic properties. It is thus effective to explain the dependences of the arc parameters on the pressure even under the different arc-conditions.

4.3 Result for Arc Power Loss and Time Constant

Figure 7(a) represents the assumed interrupting-current \( i \) during the time of \(-50 \) to 0 \( \mu \)s. The time of zero corresponds to the time at which the instantaneous current is zero. Figure 7(b) shows \( q \) obtained for different pressures. The augment in the pressure from 0.1 to 0.5 MPa decreases \( q \) at any instantaneous time.

Figure 7(c) presents the magnitude of \( q^{(i)} \) relative to \( q^{(1)} \) \((i \geq 2, 3, 5)\). As seen in this figure, the relative magnitudes for 0.2, 0.3 and 0.5 MPa are higher than 1 at a certain time and
Arc Parameters of CO₂ Arc around Current Zero

Fig. 7. Arc power loss and arc time constant derived from theoretical calculations for different pressures

Fig. 8. Enthalpy per unit volume of high-temperature CO₂ for different pressures

The relative magnitude grows with the pressure at the same instant. This fact indicates that the CO₂ arc before the current zero loses the greater power at higher pressure.

Figure 7(d) indicates the magnitude of \( \theta^{(i)} \) relative to \( \theta^{(1)} \) before the current zero \((i = 2, 3, 5)\). As seen in this figure, all of \( \theta^{(i)}/\theta^{(1)} \) are almost equal to 1 at a certain time. Thus the CO₂ arc is found to have the time constant independent of the pressure over the range from 0.1 to 0.5 MPa.

4.4 Discussion As described above, the arc was found to lose the greater power at higher pressure. This phenomenon is interpreted in terms of the enthalpy, as stated below.

The arc sustained in gas flow around the current zero principally losses the power through the convection mechanism. This loss at the same gas flow rate rises with an enthalpy of the high temperature gas. Figure 8 presents an enthalpy per unit volume of high-temperature CO₂ that has been theoretically derived. It is seen in Fig. 8 that the rise in the pressure causes grow in the enthalpy at the same temperature. This fact indicates that the arc power loss lost through the convection mechanism increases with the pressure.

On the other hand, as mentioned above, the CO₂ arc around the current zero was found to have the time constant almost independent of the pressure. This phenomenon can be understood below.

Frind has proposed that a time constant of the arc under a transient state was expressed in the form (9):

\[
\theta = \frac{\pi r_0^2}{\pi 2.4^2 \alpha} \tag{10}
\]

where \( r_0 \) is the radius of a conducting area and \( \alpha \) is a thermal diffusivity. On the basis of his theory, we will discuss the dependence of \( \theta \) on the pressure. Figure 9 shows the radial distribution of the temperature derived from the above-mentioned theoretical calculation and presents the temperature at the time of \(-30 \mu s\) as an example. Let us consider a radial position with a temperature of 5,000 K as the radius of the conducting area. As seen in this figure, the CO₂ arc has thinner radius at higher pressure in the range from 0.1 to 0.5 MPa. While, Fig. 10 indicates the thermal diffusivity \( \alpha \) as defined as \( \kappa/(\rho C_P) \tag{11} \) of the high-temperature CO₂ for different pressures. The higher pressure leads lower \( \alpha \) at the same temperature. In summary, as far as the conditions adopted in the present research are concerned, the rise in the pressure causes decline in both the arc radius \( r_0 \) and the thermal diffusivity \( \alpha \), thus seeming to result in no significant change in the time constant before the current zero.
5. Conclusions

Concerning the CO₂ arc during the current-interruption process, the arc power and the arc time constant were measured before the current zero. As far as the experimental conditions adopted in the present study, the CO₂ arc at the pressure of 0.1 MPa for 2.1 kA peak proved to show a decrease in the arc power loss from about 5 to 1.4 kW with the passage of a time from −20 to −2 μs and was found to reveal a decline in the arc time constant from about 5 to 1.5 μs with the same elapse of the time. The increase in the pressure to 0.2 MPa caused a grow in the arc power loss, but resulting no marked change in the time constant.

Theoretical calculations on the extinguishing arc under the axial CO₂ flow were made to obtain the arc parameters over the wide pressure range from 0.1 to 0.5 MPa. The calculation results showed that the increase in CO₂ pressure led to raise the arc power loss, while no longer changing the arc time constant. On the basis of theoretical calculation on the arc, above dependences of the arc power loss on the pressure proved to result from augment in the enthalpy with the pressure. In addition, the independence of the time constant on the pressure was explained in terms of the conducting radius and the thermal diffusivity.

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References


Yasunobu Yokomizu (Senior Member) received the Ph.D. degree in Electrical Engineering from Nagoya University, Japan in 1991. He was an Assistant Professor at Nagoya University in the Department of Electrical Engineering from 1990 to January 2000. Since February 2000, he has been an Associate Professor at Nagoya University in the same department. He is presently involved in the study of various phenomena and technologies related to the electric power system.

Ikuma Morooka (Student Member) received the BS and MS degrees in Electrical Engineering in 2004 and 2006 from Nagoya University, Japan. He was involved in arc interruption phenomena in environmentally benign gases.

Toshiro Matsumura (Member) received the Ph.D. degree in Electrical Engineering from Nagoya University, Japan in 1980. He was an Assistant Professor at Kyoto University in 1989. He was an Associate Professor at Nagoya University from 1992 to 1995. Since April 1995, he has been a Professor at Nagoya University in the Department of Electrical Engineering. He is currently involved in the study of high-current phenomena. He is a member of IEEE.