PAPER

Effect of Surrounding Atmospheres on Break Arc Durations of Electrical Contacts in DC Load Conditions

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SUMMARY In order to realize better understanding of influential order sequences of surrounding atmospheres on break arc durations of electrical contacts in DC load conditions, a quantitative mathematical model, which aims to indicate dependences of break arc durations on several gas parameters such as molecular mass, viscosity, specific heat capacity, thermal conductivity, electro-negativity, and ionization potential, was analyzed. Break arc durations of AgCdO contact pairs were measured in several kinds of surrounding atmospheres (N_2, Ar, He, air, O_2 and CO_2) under different DC voltage and current conditions, and data fitting processes were conducted. As a result, a candidate mathematical model was established, which could indicate possible influential order sequences of surrounding atmospheres on break arc durations in the range of the tested conditions.
key words: *electrical contacts, arc duration, break arc, AgCdO, surrounding atmosphere*

1. Introduction

Appropriate selection of surrounding atmospheres or gases in DC switching devices provides us with improved quenching abilities of break arcs, which in turn can realize improved reliabilities and electrical lifetimes of electrical contacts. This is because ignition and quenching of break arcs are likely to be greatly influenced by surrounding gases. Previous researches on arc quenching abilities of several gases can be divided into two categories: experimental studies and numerical simulation studies.

In experimental studies, Xin studied arc characteristics under 270 VDC and 6 A to 130 A, and found that arc durations in H_2 were much shorter than those in air or N_2 [1]. Hasegawa carried out breaking arc experiments in air, Ar and N_2 at 0.1 MPa, and showed that the average breaking arc duration in Ar (0.360 ms) was closed to that in air (0.375 ms), but longer than that in N_2 (0.260 ms) [2]. Zhou conducted breaking arc experiments with applied magnetic field of 30 mT in air and N_2 at atmospheric pressures from 0.1 MPa to 0.25 MPa, and concluded that the average breaking arc duration in air was longer than 3.3ms, while that in N_2 was less than 3ms under the condition of 300 Vdc and 100 A [3]. Takahashi studied influences of organic compound atmospheres on electrical endurance characteristics with AuAg alloy contacts, and found that contact lifetimes at 15 VDC and 0.53 A were with the following sequence: tetrahydrofuran < methanol < 2-propanol < formic acid [4]. Yoshida conducted the experiment with four surrounding gases of clean air, N_2, He and H_2 under the source voltage 100 VDC and closed currents 1-30 A, and showed arcing duration sequence is H_2 < N_2 < Air < He [5].

With respect to numerical simulations on influences of surrounding gases, Zang studied densities of multiple particles such as N_2, N_2+, N, O_2, O_2+ and O with different proportions of O_2-N_2 mixtures at different arc temperatures through simulation [6]. Specifically, under different breaking speeds, arc characteristics in N_2 were simulated at 28 VDC and 20 A to 60 A. The obtained results indicated that arc durations were likely to become longer with existence of silver vapors [7]. Liu calculated breaking capacity in SF_6-N_2 mixtures with Patankar-Spalding method, and pointed out that the breaking capacity in the mixture of 60% SF_6 and 40% N_2 would be deteriorated to the level corresponding to about 80% of that in pure SF_6 condition [8]. Oh showed that the composition of surrounding gas CO_2 is a function of temperature and there are no CO_2 molecules within the plasma if the dissociation and ionization increases due to the increased temperature. Radiative heat transfer (RHT) is a very large factor in determining the temperature of arc plasma, while also greatly affecting the properties of the dielectric gas [9]. Lindmayer indicated that the power removal in the bulk of arc zone occurs mainly by strong convection, caused by the electromagnetic pump formed by the transverse magnetic field together with the arc current, heat conductivity of gas is only of minor important [10]. Zhao calculated the arc interruption performance of SF_6-CO_2 mixtures based on Mayr equation [11]. Rong simulated the internal fault arc in a closed container with the consideration of specific heat and molar mass of gas [12].

Summarizing the results in the above-mentioned literatures, up to now, there are quite few reports on both experimental data of DC arcing durations in different surrounding atmospheres, and theoretical correlation between physical parameters of atmospheres and arcing durations. Hydrogen has a high ability of arc quenching, which is explained as the high heat conduction loss of arc column energy caused by high thermal conductivity of hydrogen in [5], however it is interpreted as convection loss of plasma power caused by the electromagnetic pump [10]. Therefore, the mechanism

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on how surrounding gases will affect arc extinction still needs further studies.

Different arcing durations in different gases are basically resulted from differences in their physical parameters, and thus, it is of great significance to establish a mathematical model which can show relationship between gas parameters and the arcing durations based on the experimental data in different atmospheres under DC voltage.

Li Chen and Li Zhenbiao, et al., introduced a candidate mathematical model for indicating relative degrees of influences of surrounding atmospheres on break arc durations with the experimental conditions 14 V–42 V/5 A–30 A and 5 gases N_2, He, CO_2, Ar, air [13]. More specifically, they tried to obtain a mathematical model showing certain relative relationships between break arc durations and several parameters of surrounding atmospheres such as U_i (ionization potential), m (relative molecular mass), ρ (density), η (viscosity), C_p (specific heat capacity), κ_ω (thermal conductivity), and χ (electro-negativity). Their model was intended to be used for comparisons of arc quenching capabilities of different surrounding atmospheres rather than calculation of exact values of break arc durations.

The above model in Li's paper [13] was based on its test conditions (14–42 VDC and 5–30 A), and it may not be applicable in conditions outside the above range since the values of gas parameters are affected by conditions such as arcing currents. Therefore, further experiments with higher currents (37.8–88.5 A) and more gases (adding O_2 as another gas) were conducted in [14] and its model showed that the calculated relative sequences of arc quenching abilities were conformed to the experimentally determined sequences with the percentage of 83.3% (i.e. 5 gases in 6). In other words, the model in [14] needs further improvements in order to obtain the ideal value of 100%.

In view of the above, in this paper, the present authors tried to develop a better model through data fitting processes, and also tried to find out how gas parameters will affect arcing durations based on the obtained results [13], [14].

2. Experimental Procedures

Figure 1 illustrates a circuit diagram of the experimental circuit for performing break arc duration measurements, while Fig. 2 shows a schematic diagram of a make/break operation mechanism for a test contact pair. Figure 3 show changes in an opening speed of the movable contact over time during breaking operations. In addition, Table 1 shows the experimental conditions where the open and close speeds are measured by the displacement sensors in Fig. 2. Table 2 shows the load circuit conditions, in which the current value is varied in the range of 30-100 A so that the data fitting model can be adapted to a wider range.

This circuit includes a DC power supply E of 270V/100A, a pair of test electrical contacts K, two adjustable resistors R and R1, and another DC power supply E1 of 24 V. Voltage dividers 1 and 2 are also provided in order to respectively measure voltage levels UB1 and UB2

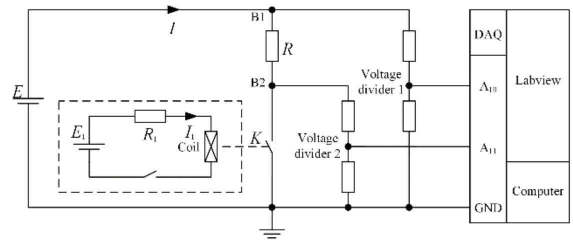


Fig. 1 Circuit diagram.

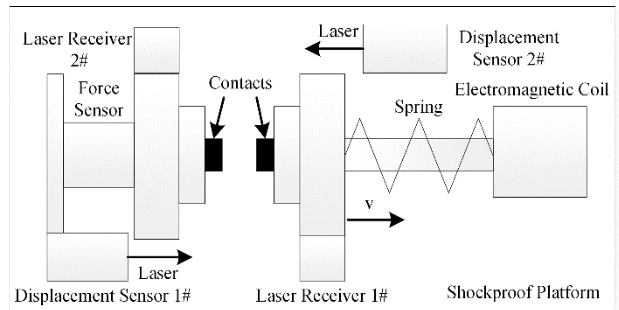


Fig. 2 Schematic diagram of the make/break operation mechanism for a test contact pair.

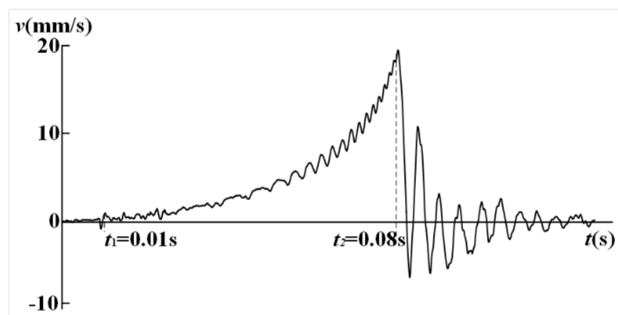


Fig. 3 Breaking speed of the dynamic contact

Table 1 Experimental conditions

Gap length (mm)	Maximum contact force (N)	Stable contact force (N)	Maximum open speed (mm/s)	Maximum close speed (mm/s)
2.7	100	25	20	25

Table 2 Load circuit conditions

E (V)	14	28	42
I (A)	39.5	37.8	39.9
	54.5	51.4	44.0
	88.5	62.0	56.5
	-	80.2	64.7
	-	-	77.2

at points B1 and B2. Measurement of the voltage at B1 was conducted to obtain an exact voltage level UB1 at B1 that may not be equal to the voltage level supplied from the power supply E due to possible voltage drop along wirings and terminals. A load current level I flowing through the test contact pair K can be determined as I = (UB1-UB2)/R.

An operating cycle was set as 1 second on and 2 seconds off. A moving contact was set as an anode. Make/break operations of the test contact pair were realized by means of a spring and an electrical coil, respectively. During the breaking operations, the speed of the dynamic contact, as shown in Fig. 3, started increasing from 0 at the moment t_1 to the maximum of 20mm/s rapidly within 0.07s with an increasing acceleration. The contact was then stopped by a back plate mounted on the mechanism at the moment t_2. Vibrations caused by the collision against the back plate are visible in the waveform with swift fluctuations after t_2.

The total of 18 pairs of rivet-type AgCdO contacts (with a head-diameter of 10mm and a thickness of 3mm) were used, and named as 1#-18#. AgCdO contacts are still broadly used in various switching mechanisms and relays, e.g., in U.S., irrespective of the RoHS Directive, because the material exhibit outstanding switching performances under high power load conditions. Thus, it is still worth investigating switching characteristics of AgCdO contacts for manufactures of commercial relay products. Those 18 pairs of test contacts were divided into 6 groups (with 3 pairs in each group). Each of the 6 groups was used for experiments in N_2, He, O_2, Ar, CO_2 and air, respectively. More specially, 1#-3# in air; 4#-6# in N_2; 7#-9# in Ar; 10#-12# in He; 13#-15# in CO_2; and 16#-18# in O_2.

Before starting the respective experiments, the make/break operation mechanism shown in Fig. 2 was put into a chamber, and the air in the chamber was evacuated with an adsorption pump to 10^{-4} Pa. Thereafter, the chamber was filled with one of the gases to the atmospheric pressure level and then sealed until the end of the experiment.

Each of the test contact pairs was operated to conduct make/break operations in the test circuit as shown in Fig. 1 up to 50 times under each of the load conditions as listed in Table 2, starting from 14 V–39.5 A and then successively with the two other current levels at 14 V, then 28 V–37.8 A and further until 42 V–77.2 A. Once contact welding occurred, which means the movable contact can not be separated by the excited coil and the two contacts will keep connected together always, the make/break operations were ended. Otherwise, the make/break operations were successively repeated until the 50 operations at 42 V–77.2 A were safely finished. During the operations, contact voltage waveforms and current waveforms were recorded by virtual instrumentation based on a contact simulation test device. Average break arc durations in the respective test conditions were calculated by way of a calculation program that was prepared based on LabVIEW software after the experiments.

3. Measured Results on Break Arc Durations under the Respective Test Conditions

Three pairs of test contacts were operated in each of the test conditions (specifically, combinations of the surrounding atmospheres, the voltage levels and the current levels). Thus, average break arc durations $\overline{t_m}$ in the respective test conditions were calculated in accordance with (1) as indicated below. In this equation, $t_{i,1}$, $t_{i,2}$ and $t_{i,3}$ represent the breaking arc duration of the i-th operation of the first, second and third test contact pairs in the corresponding gas, respectively.

$$\overline{t_m} = \frac{1}{3}\left(\frac{1}{50}\sum_{i=1}^{50} t_{i,1} + \frac{1}{50}\sum_{i=1}^{50} t_{i,2} + \frac{1}{50}\sum_{i=1}^{50} t_{i,3}\right) \quad (1)$$

Table 3 shows the obtained average breaking arc durations at each of the test conditions.

Figure 4 shows exemplary actual measured values of break arc durations during the 50 operations under specific voltage and current conditions for the sample 3# in air and the sample 4# in N_2. As shown in this figure, at each of the voltage and current conditions, the measured values of break arc durations are not likely to show any trends of monotonous rise or decrease with increased number of operations. In addition, the actual measured values of break arc durations were likely to show some fluctuations around the corresponding average value. From those aspects, influences of different surrounding atmospheres on break arc durations can be discussed based on the average break arc durations over the certain number of operations.

As shown in Table 3, in different surrounding atmospheres, average values of the measured break arc durations at DC 14 V with all of the current levels can be listed in a sequence as follows: He $<$ O_2 $<$ CO_2 $<$ N_2 $<$ air $<$ Ar.

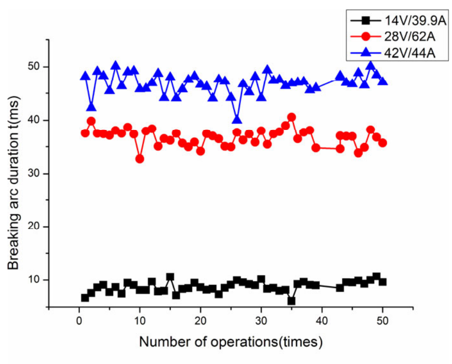
Table 3 Average values of the measured break arc durations in the respective test conditions

Voltage (V)	Current (A)	Air	N_2	Ar	He	CO_2	O_2
14	39.5	9.60	8.09	29.18	3.34	5.54	4.37
	54.5	14.53	8.88	30.84	4.59	6.55	4.83
	88.5	17.92	10.43	31.65	5.99	8.05	6.10
28	37.8	34.36	18.01	74.56	15.08	19.44	20.67
	51.4	36.95	19.34	161.17	16.76	21.02	22.13
	62	46.72	20.17	-	17.73	21.80	23.50
	80.2	45.30	21.23	-	17.91	23.51	26.10
42	39.9	54.06	26.26	-	45.42	-	-
	44	60.98	27.61	-	82.69	-	-
	56.5	-	44.61	-	-	-	-
	64.7	-	46.14	-	-	-	-
	77.2	-	46.99	-	-	-	-

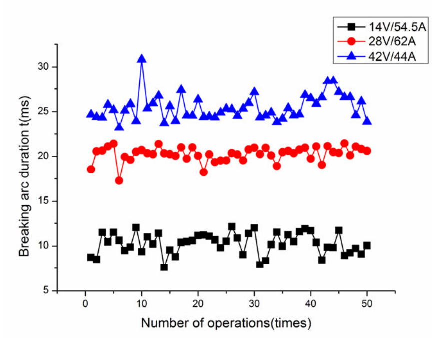
Note: the mark"-" means that the welding appears in this condition, and therefore, there are no further experimental data.

However, at DC 28 V with all of the current levels, averages of the measured break arc durations can be listed in a different sequence as follows: He < N_2 < CO_2 < O_2 < air < Ar. These sequences indicate that influences of atmospheres on arc quenching become different with voltage levels, and natures of atmospheres have an important effect on arcing durations because different atmospheres have different physical parameter values as shown in Table 4.

Specifically, at higher voltage levels (28 V in this test), the arc quenching ability of N_2 can be enhanced while that in O_2 is weakened. Moreover, in the 42 V operations, N_2 exhibited the best arc quenching ability among the six surrounding atmospheres in this study, and no welding was observed in N_2, while welding often occurred in the other five atmospheres [13]–[15]. The contact welding mechanism is introduced in previous Refs. [16], [17].



(a)



(b)

Fig. 4 Exemplary actual measured values of break arc durations during the 50 switching operations. (a) 3# in air; (b) 4# in N_2.

4. Relationships between Parameters of the Surrounding Atmospheres and Break Arc Duration Characteristics

As shown in Table 3, the measured break arc durations were influenced by the surrounding atmospheres even with the same voltage and current levels. Such tendencies can be believed to be related to some parameters of the respective gases.

Generally, gas within the hermetically sealed house is heated by contact arcing. Its real-time parameters values, which are strongly dependent on temperature, density, composition of gas particles and initial value of gas parameter at room temperature etc., are almost impossible to be exactly known since real-time internal chemical/physical interactions between particles in arcing column and surrounding gas, which are closely dependent upon arcing current and supply voltage, could not be described quantitatively, including gas particle (molecular or atom) dissociation, collision, ionization, re-ionization and recombination. Therefore, in this paper, different function forms are compared so as to selected a better one that can describe effects of gas parameters on arcing durations.

Table 4 summarizes values of several physical parameters of the six gases, employed in this study, at room temperature. In the table, m, η, C_v, κ_ω, χ, and U_i respectively represents relative molecular mass, viscosity, specific heat capacity, thermal conductivity, electro-negativity, and molecular ionization potential. Those parameters can be taken into account for the purpose of establishing certain mathematical relationships that can predict possible influences of surrounding atmospheres (gases) on break arc durations, as follows [13]:

1) m (relative molecular mass)

A value of a relative molecular mass of gases is clearly related to a velocity of gas molecules. Gas molecules with a smaller value of m (relative molecular mass) can move faster under the same temperature, which can in turn lead to better diffusibility and thus help accelerating arc extinction.

2) η (viscosity)

A value of a viscosity of gases is related to a degree of macro liquidity of the gases [19]. Higher viscosity means that surrounding gas of a lower temperature has longer time to absorb more energy from an arcing column of a higher

Table 4 Physical parameters of the six surrounding atmospheres employed in this study at 25 degrees celsius [13], [18].

Parameters \ Gases	Air	N_2	Ar	He	CO_2	O_2
M	29	28	40	4	44	32
$\eta(10^{-7}$Pa·s)	183.7	175.44	224.42	186.4	137.3	201.74
C_v(J/(g·K))	0.72	0.741	0.312	3.116	0.684	0.661
κ_ω(W/(m·K))	0.0259	0.0248	0.0179	0.1426	0.01645	0.02571
χ(eV)	7.97	7.95	8.01	6	8.64	9.62
U_i(V)	15	15.5	15.7	24.6	13.7	12.8

temperature, thus lowering the temperature of arcing column, which can make arc extinction easier. On the contrary, higher viscosity decreases the gas diffusibility and slows down particles spread, which may increase the arcing duration. The above two effects exist simultaneously.

3) C_v (specific heat capacity)

A larger value of specific heat capacity of gas means possible smaller increases of gas temperature with the same amount of arc energy. Therefore, this may lead to a lower amount of kinetic energy of gas molecules and lower possibility of their ionization, which may in turn make arc extinction easier.

4) κ_ω (thermal conductivity)

With a larger value of κ_ω, heat can be easily and rapidly transferred from an arc column to electrodes and/or ambient gases. This may result in two effects, one is beneficial to reduce the arcing column temperature through the quick heat transfer, and the other is to increase the electrodes temperature or vaporization. The former is helpful to arc extinction, but the latter is opposite.

5) χ (electro-negativity)

High electronegativity of gas is usually considered to cause high dielectric strength and good arc quenching ability. For example, one of the reasons why SF_6 is widely used in high voltage switchgear is its high electronegativity [20]. So the electronegativity is selected to be a gas parameter in the model.

6) U_i (ionization potential)

A value of ionization potential indicates how easily gas molecules can be ionized. This can be considered to have certain influences on maintaining arc column.

In the previous work done by Li et al. [13], a density of gases was also selected for candidate parameters when establishing their mathematical model. However, a gas density is clearly related to a relative molecular mass (already selected as in the above), and thus omitted here.

In addition, with respect to the specific heat capacity, different from the previous work by Li et al. [13], in which C_p (specific heat capacity at constant pressure) was used, C_v (specific heat capacity at constant volume) was decided to be used here since the gas volume in chamber is constant but its pressure may be changed due to the heating effect of arcing in this experiment.

By employing those six parameters of surrounding atmospheres, in addition to voltage U and current I, a certain mathematical model for predicting degrees of influences (also referred to as influential order sequence) of surrounding atmospheres (gases) on break arc durations was searched through data fitting procedures.

How to determine the form of the fitting function is the key of building the model. A general-purpose form of model should be in the form shown as (2), which indicates the arcing duration of gas is related to source voltage, current and gas properties. It should be noted T represents relative degrees of break arc durations which is used to make comparisons among the results in different test conditions and obtain influential order sequence of surrounding atmospheres on break arc durations.

$$T = f(U, I, m, \eta, C_v, \kappa_\omega, \chi, U_i) \tag{2}$$

Firstly, it was assumed in [13], [14] that each of those six gas parameters (m, η, C_v, κ_ω, χ, and U_i) as well as voltage U and current I were independent from each other. Secondly comparing the consistency between the model (2) and the experiment indicated that the power function (2) is better than polynomial and exponential. So a possible model was expresses as (3), Finally The data fitting was conducted by calling a regress function in MATLAB, and values of α_1 through α_8 as well as β in (3) were determined, calculation with (3) indicated its result was of worse consistency with the experiment.

$$T = \beta \cdot U^{\alpha_1} \cdot I^{\alpha_2} \cdot m^{\alpha_3} \cdot \eta^{\alpha_4} \cdot {C_v}^{\alpha_5} \cdot {\kappa_\omega}^{\alpha_6} \cdot \chi^{\alpha_7} \cdot {U_i}^{\alpha_8} \tag{3}$$

To find an improved model, Eq. (2) was modified as (4), where, the parameters of η, C_v and κ_ω, are assumed to be composite variables of the voltage U and the current I [14]. It should be noted that the above composite form for parameters, such as $\eta(U, I)$, does not represent the absolute value of the parameters in arcing. It mainly indicates the mathematic relationship between the breaking arc duration and gas parameters in different supply voltage and load current. Further assuming that (4) has the form of power function as in the previous case, it is showed in (5). The calculation with (5) showed that the degree of consistency between experiment and model is 83.3%, and CO_2 is inconsistency.

$$T = f(U, I, m, \eta(U, I), C_v(U, I), \kappa_\omega(U, I), \chi, U_i) \tag{4}$$

$$T = \beta \cdot U^{\alpha_1} \cdot I^{\alpha_2} \cdot m^{\alpha_3} \cdot \eta^{\alpha_{41} U + \alpha_{42} I} \cdot {C_v}^{\alpha_{51} U + \alpha_{52} I} \cdot {\kappa_\omega}^{\alpha_{61} U + \alpha_{62} I} \cdot \chi^{\alpha_7} \cdot U_i^{\alpha_8} \tag{5}$$

In order to find a better model which can approach 100% consistency, the function (4) was modified as (6), where each of the parameters m, η, C_v, κ_ω, χ and U_i is assumed to be composite variable of itself and the voltage U. Arcing current has minor influence on the sequence of arcing duration in different gases, which can be found in Table 3 and also confirmed in [13], [14], so current is not listed as internal variables of gas parameters in (6).

$$T = f(U, I, m(m, U), \eta(\eta, U), C_v(C_v, U), \kappa_\omega(\kappa_\omega, U), \chi(\chi, U), U_i(U_i, U)) \tag{6}$$

Further assuming that (6) has the form of power function as in the previous cases, it can be expressed as (7):

$$T = \beta \cdot U^{a_1} \cdot I^{a_2} \cdot m^{a_3 U + a_4 m} \cdot \eta^{a_5 U + a_6 \eta} \cdot {C_v}^{a_7 U + a_8 C_v} \cdot {\kappa_\omega}^{a_9 U + a_{10} \kappa_\omega} \cdot \chi^{a_{11} U + a_{12} \chi} \cdot U_i^{a_{13} U + a_{14} U_i} \tag{7}$$

The data fitting was conducting by calling a regress function in MATLAB software package and a least square method was used. The mathematical models based on (7) was obtained, which can be expressed as (8) below:

Table 5 Values of T obtained from (8)

Voltage(V)	Current(A)	Air	N_2	Ar	He	CO_2	O_2
14	39.5	13.81	7.62	26.20	3.77	5.82	3.96
	54.5	15.75	8.69	29.87	4.29	6.63	4.51
	88.5	19.18	10.59	36.39	5.23	8.08	5.50
28	37.8	32.06	17.34	142.20	14.97	19.08	21.86
	51.4	36.34	19.66	161.17	16.96	21.62	24.78
	62	39.22	21.22	-	18.31	23.34	26.75
	80.2	43.56	23.56	-	20.33	25.92	29.70
42	39.9	60.62	32.15	-	48.45	-	-
	44	63.09	33.45	-	50.42	-	-
	56.5	-	37.04	-	-	-	-
	64.7	-	39.15	-	-	-	-
	77.2	-	42.07	-	-	-	-

Note: the mark”-” means that the welding appears in this condition, and therefore, there are no further experimental data.

Table 6 Comparison between arc duration sequences of experimental results and results from (8)

Voltage (V)	Current (A)	Sequence		Correspondence
		Experimental results	Results from (8)	
14	39.5	$He<O_2<CO_2<N_2<Air<Ar$	$He<O_2<CO_2<N_2<Air<Ar$	Yes
	54.5	$He<O_2<CO_2<N_2<Air<Ar$	$He<O_2<CO_2<N_2<Air<Ar$	Yes
	88.5	$He<O_2<CO_2<N_2<Air<Ar$	$He<O_2<CO_2<N_2<Air<Ar$	Yes
28	37.8	$He<N_2<CO_2<O_2<Air<Ar$	$He<N_2<CO_2<O_2<Air<Ar$	Yes
	51.4	$He<N_2<CO_2<O_2<Air<Ar$	$He<N_2<CO_2<O_2<Air<Ar$	Yes
	62	$He<N_2<CO_2<O_2<Air$	$He<N_2<CO_2<O_2<Air$	Yes
	80.2	$He<N_2<CO_2<O_2<Air$	$He<N_2<CO_2<O_2<Air$	Yes
42	39.9	$N_2<He<Air$	$N_2<He<Air$	Yes
	44	$N_2<Air<He$	$N_2<He<Air$	No

Note: comparison under 42V/56.5A, 42V/64.7A and 42V/77.2A is not given because only the data of N_2 are available in these cases.

$$T = \frac{10^{9.3814} U^{0.8519} I^{0.4074} m^{0.248U+0.001m} \kappa_{\omega}^{0.513U} \chi^{0.8075U-0.8692\chi} U_i^{0.585U-0.2705U_i}}{\eta^{0.4396U-0.0026\eta} C_v^{0.2723U-0.9279C_v}} \tag{8}$$

From (8), the values of T under the respective test conditions were calculated. The results are summarized in Table 5.

In order to confirm the validity of the established model (8), a comparison of the sequences of arc durations in different atmospheres between the tested values (according to Table 3) and the data-fitting ones (according to Table 5) is made in Table 6. As shown in Table 6, the calculated sequence of the arc quenching abilities of the surrounding atmospheres was conformed to the experimentally determined sequence with respect to all the experimental gases in every voltage and current condition only with one exception for case of air in 42 V/44 A, which indicates a precision of 88.9% (both sides coincide with each other in 8 of 9 cases). For example the calculated sequences in 14 V and 28 V in Table 5 are corresponding to He $<$ O_2 $<$ CO_2 $<$ N_2 $<$ air $<$ Ar, and He $<$ N_2 $<$ CO_2 $<$ O_2 $<$ air $<$ Ar respectively, which are identical to experiment results in Table 3.

Therefore, the model (8) can show influences of the surrounding atmospheres on break arc duration characteristics at least in the range of this test condition. By employing this model, we can predict or assume to some extent whether a certain surrounding atmosphere can provide us with an improved arc quenching ability (in other words, shorter break arcs).

5. Discussion

Generally, the data fitting model is valid only for the range where the experimental data exist, so extrapolation to outside range cases should be done carefully. For example, parameters values in mixed gases are much more complicated than pure gases. Arcing duration is affected by many factors including opening velocity, gap length and contact materials (For instance, with a faster breaking velocity and a larger gap length, the arcing time is likely to be obviously shortened because arcs reach the limited length for its burning considerably quicker, making it more difficult to be sustained). Meanwhile it is found that experimental data for breaking arc durations in different gases, voltage and current levels, opening velocities and gap lengths are reported quite a little until nowadays, and thus, more experiments are needed to be done in the future.

Experiments in this paper, in which a load current is switched at both making and breaking operations, are corresponding to real operation status, but contacts are easier to be welded, leading to less arcing data. The welding occurs generally at make operations. Thus, experiments in which a load current is controlled not to flow through a test contact pair at their making operations will have less welding occurrences and more arcing duration data. This will be helpful to the data fittings. Future experiment will be done in that way.

It should be also noted that the contacts did not weld only in N_2. Such a tendency will be intensively related to the resultant arc duration characteristics. Specifically, in

Table 7 Positive and negative relationship between the gas parameters and the arc durations T

Gases	Voltage (V)	dT/dm	$dT/d\eta$	$dT/d\kappa_\omega$	dT/dC_v	$dT/d\chi$	dT/dU_i
	14	+	-	+	-	-	-
Air	28	+	-	+	-	+	+
	42	+	-	+	-	+	+
	14	+	-	+	-	-	-
N_2	28	+	-	+	-	+	+
	42	+	-	+	-	+	+
	14	+	-	+	-	-	-
Ar	28	+	-	+	-	+	+
	42	+	-	+	-	+	+
	14	+	-	+	+	-	-
He	28	+	-	+	-	+	-
	42	+	-	+	-	+	-
	14	+	-	+	-	-	-
CO_2	28	+	-	+	-	-	+
	42	+	-	+	-	+	+
	14	+	-	+	-	-	-
O_2	28	+	-	+	-	-	+
	42	+	-	+	-	+	+

Table 6 the break arc duration in N_2 under 28V and 42V, where welding occurs in the other 5 atmospheres, is relatively shorter and even the shortest, which means smoother morphology with fewer, smaller melting pools and bridges on the contact surface being likely to be produced during arcing. A tough and unbreakable metallic bond to be produced between the mating contacts by melting pools and bridges after solidification are generally considered as the main reason of dynamic welding. Thus, it can be explained why N_2 reduces the welding risk [21].

The function form of data fitting model is not as rigorous, exact and unique as the model received from mathematical equations derivation; correspondingly, the physical meaning or mechanism of the former model is not as exact as latter. But the data fitting model can still indicate some interesting physical meaning or mechanism to show how and in what degree the arcing duration is affected by the gas parameters, current and voltage respectively. For examples, the power values of current in Eq. (8) is 0.4074 which is much less than the corresponding values of voltage 0.8519. The above phenomena means that the current play less important role than supply voltage in breaking arc duration. On the other hand, Eq. (8) indicates gas parameter value in arcing is strongly correlated with both supply voltage and parameter itself, which illustrates the chemical and physical complexities inside the arcing column and surrounding gas.

Equation (8) may also help to understand the positive or negative role of gas parameters in arcing extinction, therefore the partial derivative dT/dP (P denotes the parameters m, η, C_v, κ_ω, χ, and U_i) was computed with (8) to show whether each parameter has a positive or negative correlation. For example, the results of dT/dm and $dT/d\chi$ were listed respectively in the following (9) and (10).

$$\frac{dT}{dm} = k_1 \cdot m^{0.001m+0.248U}\left(0.001 \ln m + 0.001 + \frac{0.248U}{m}\right) \quad (9)$$

$$\frac{dT}{d\chi} = k_2 \cdot \chi^{0.8075U-0.8692\chi}\left(-0.8692 \ln \chi - 0.8692 + \frac{0.8075U}{\chi}\right) \quad (10)$$

The results for all of the six parameters were listed in Table 7, where "+" and "-" denotes the sign of the values are positive or negative, respectively, which correspond to the positive or negative correlations. Positive (negative) means the higher the parameter value is, the longer (shorter) the arcing duration is.

Table 7 shows that dT/dm and $dT/d\kappa_\omega$ are always positive values, which mean that the smaller values of m and κ_ω will result in shorter arcing durations. On the other hand, $dT/d\eta$ shows always negative values, which represents the smaller values of η will result in longer arcing durations. The signs of the other three derivatives dT/dC_v, $dT/d\chi$, dT/dU_i are changed in accordance with increases in the supply voltage, which denotes that the arcing duration is not monotonously changed with the increase of parameters C_v, χ, U_i, which is due to complicated changes in ionization, deionization and chemical reactions in the plasma and the gases.

Usually it is considered that higher heat conductivity of surrounding gas may be better for the arcing column heat dissipation and reduction of arcing column temperature and then make the breaking arcing duration shorter [5]. However the above idea is mainly considering the power loss of arcing column through the heat conduction to both the electrodes and surrounding gas, but in fact the temperature of arcing column is much higher than that of surrounding gas, so the power loss of arcing column through radiation and convection is very important even dominant [9], [10]. Therefore the effect of gas on arcing duration should consider the comprehensive roles of many parameters of gas not only thermal conductivity.

Arcing duration is connected with contact erosion and degradation, but their relationship is not monotonous [22]. For example, in the experiment 270VDC/100A with surrounding gas air and N_2, the value sequence of anode mass erosion in N_2 is CuCr40 < CuCr45 < CuCr50, but the breaking arc duration sequence is different as CuCr50 < CuCr40 < CuCr45. The sequence of anode mass erosion in air for CuW is CuW60 < CuW70 < CuW90, but the breaking arc duration sequence is different as CuW90 < CuW70 < CuW60 [22]. When all experimental conditions are exactly same except the surrounding gas, the arcing duration difference should be mainly due to the effect of gas, i.e. the difference of gas parameters. Therefore the contact erosion is not discussed in this paper.

To verify the extrapolation validity of the model (8), experimental data in [23] were used to check and showed that calculated sequence of arcing duration values with (8) is identical to the experimental sequence of 4 gases among the 5 in [23] with the conditions 100 VDC/2 A-30 A, i.e. O_2 > air > N_2 > H_2 except for the He. To make the model valid in wide range more experiments in higher voltages or currents are needed in future.

6. Conclusions

For the purpose to explain quantitative relationships between breaking arc durations and physical parameters of the surrounding atmospheres (in other words, influential order sequences of the surrounding atmospheres on break arc duration characteristics), experiments for break operations of electrical contacts in N_2, He, CO_2, O_2, Ar and air were conducted in DC load conditions with 14 V to 42 V and 37.8 A to 88.5 A. Break arc durations were measured and average values under each of the test conditions was calculated. Based on the obtained average break arc durations, data fitting procedures were conducted and optimized. As a result, the followings were made clear.

1) N_2 exhibited the best arc quenching ability with higher voltage level. For example, the sequence of the average breaking arc durations with 14 V was O_2 < CO_2 < N_2, while with 28 V, the sequence was N_2 < CO_2 < O_2. The sequence of arc quenching abilities of different surrounding atmospheres is likely to change with increased voltage levels.

2) Load current play less important role than source voltage for arcing duration sequence in different gases. A new mathematical model was introduced to explain the relationships between the several parameters of the surrounding atmospheres and breaking arc durations. The obtained mathematical model could show influential order sequences of the surrounding atmospheres on break arc duration characteristics and evaluate whether a certain surrounding atmosphere may provide us with an improved arc quenching ability (shorter break arc duration).

3) The relationships between physical parameters of surrounding atmospheres and average break arc durations are complex and nonlinear. Gas parameter values in arcing is found to be related to both the supply voltage and the parameter itself.

4) The relative molecular or atom mass, thermal conductivity are positively correlated with arcing duration, but viscosity is with negative. The specific heat capacity, electro-negativity, and molecular ionization potential are not monotonously correlated with arcing duration.

It should be noted that the effect of physical parameters of surrounding gas is very complicated and strongly connected with test conditions, so more experiments are needed for better understandings.

In addition, although the mathematical fitting model equation obtained through the data fitting procedure in this paper can realize satisfactory agreements between the experimental results and the data-fitting results, reasonable explanations on meanings of the mathematical model, based on actual physical phenomena and arc behaviors, are not yet fully established. Basically, it is very difficult to establish a perfect simulation model for arc phenomena, because many factors have to be considered. However, since the mathematical fitting model can provide us with some indications on which gas parameters will play a more important role than the others for determining arcing duration characteristics in different gases, a better physical model for describing arcing phenomena in different gases will be able to be investigated and established. Such investigations remain as the subjects of further studies.

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