WHITE PAPER

GAS FILLING IN SEALED DC CONTACTOR

Comparison between nitrogen filling and hydrogen filling

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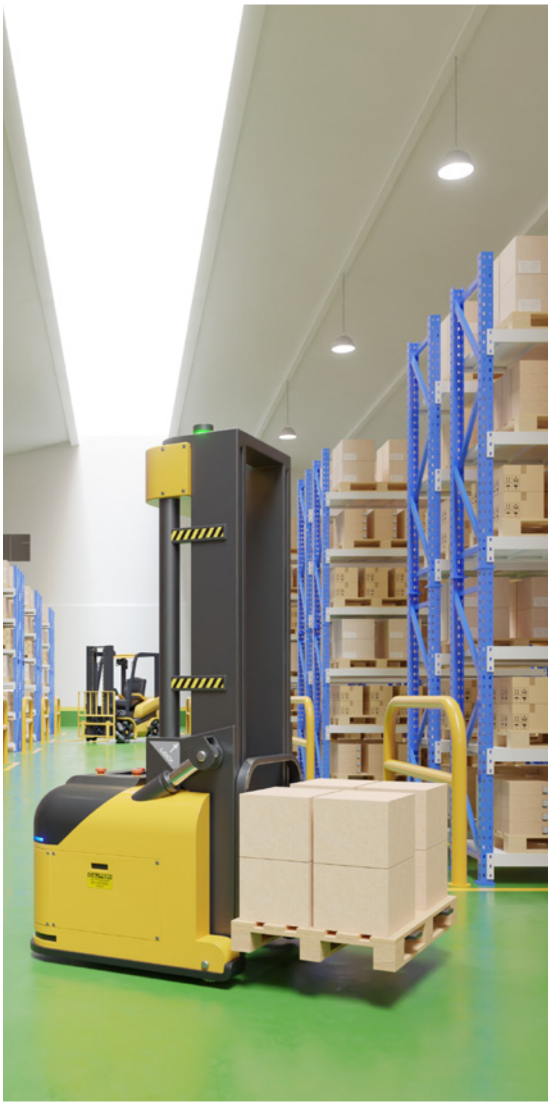
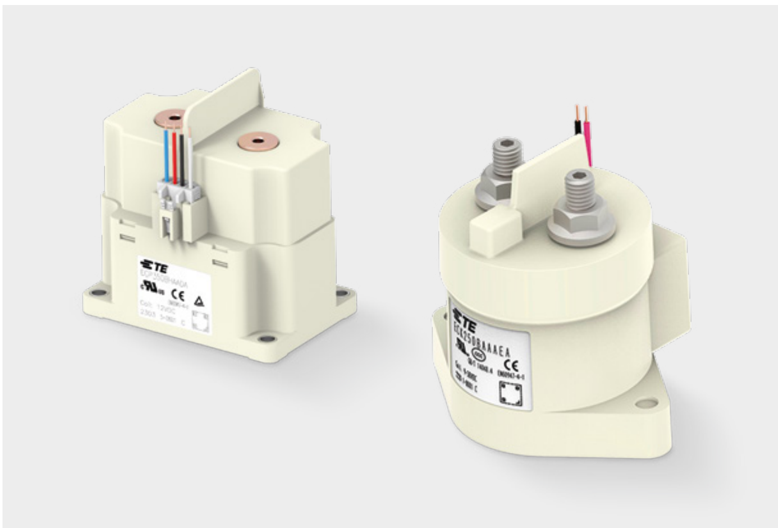
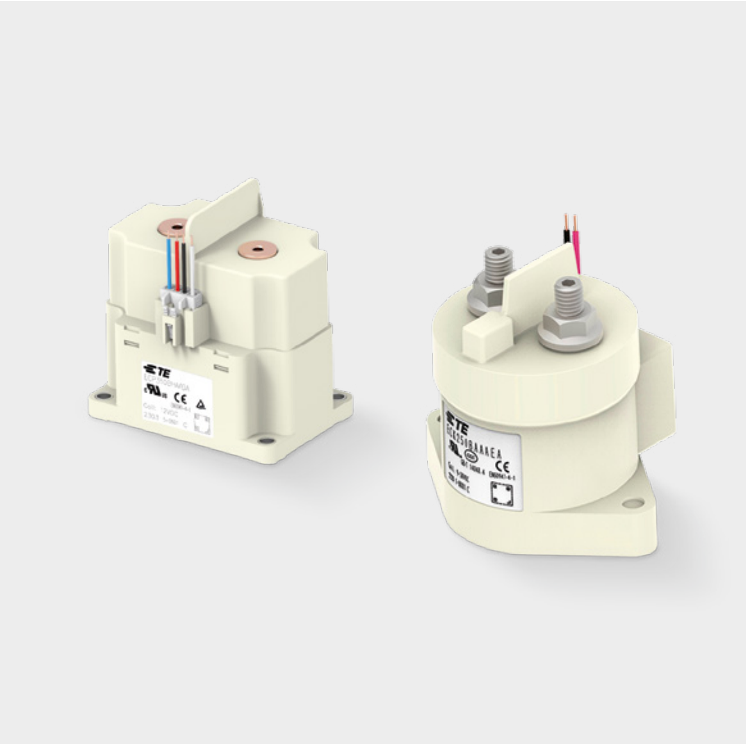




WHY DO HIGH-VOLTAGE DC RELAYS NEED TO BE FILLED WITH GAS?

What is the arc extinguishing principle of gas? Why are ceramic seals filled with hydrogen gas, while epoxy seals filled with nitrogen gas?



The increasing demand for DC contactors and the evolution of their application has impacted their requirements and has driven the development of DC contactors capable of switching higher voltages and greater currents. TE Connectivity (TE) as one of the first providers of DC contactor products in the market is continuously introducing new DC contactor products to support the evolving requirements. Increasing the switching performance while maintaining similar small sizes requires filling the contact chambers with gas to reliably extinguish the increasingly energetic electric arcs of DC loads with higher voltages and greater currents. The most frequently used gas media are nitrogen and hydrogen and a mixture thereof. The following paper analyzes and compares the differences between nitrogen and hydrogen fillings of DC contactors.

1. Introduction

High voltage DC contactors are widely used in renewable energy generation systems, electric vehicle charging stations, industrial automation, and power systems. The rapid growth of the renewable energy and electric vehicle markets has led to an increasing demand of DC contactors.

The key factors of modern high-voltage contactors are their small size, light weight, and high-performance switching capability. To reach this, DC contactors require gas filling to achieve excellent arc extinguishing characteristics while keeping their volume as small as possible.

Filling inert high-pressure gas media can maintain good dielectric strength properties and protect the contacts from oxidation in high-voltage DC contactors. It can avoid high-temperature burning of the contacts during load switching of high-voltage DC contactors and the switching performance is not affected by the external environment. This paper describes and compares the arc generation capabilities exhibited by different gas media.

2. Arc extinguishing conditions and process

First, the process of generating and extinguishing an arc is explained. During the switching process, an arc is generated between the contacts of the switch. The higher the voltage and current, the greater the arc energy, and the more difficult it is to extinguish the arc.

2.1 AC arc extinguishing conditions and extinguishing process

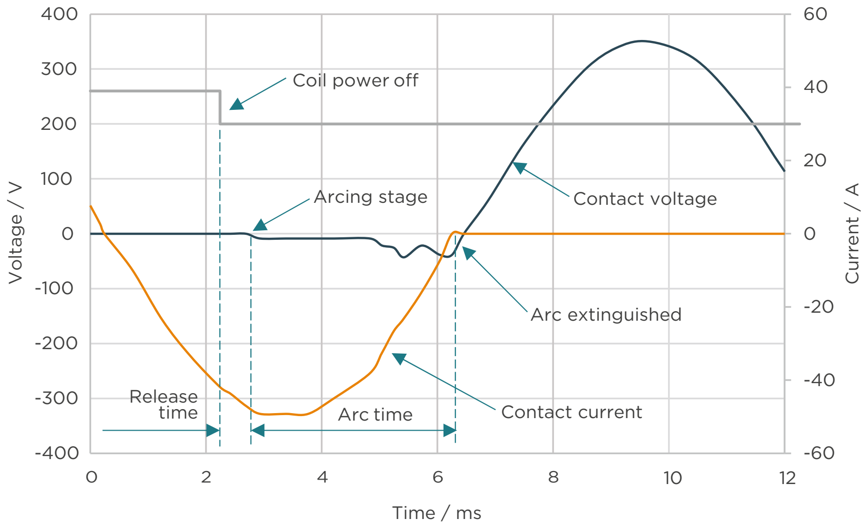


Fig.1 AC circuit breaking wave-form

An advantage of AC circuits is the natural zero crossing of voltage and current which helps to extinguish an arc. In DC circuits however, voltage and current do not have a natural zero crossing, therefore the DC contactor must make use of the voltage and current phenomenon present while breaking DC loads and additional arc extinguishing features.

2.2 DC arc extinguishing conditions and extinguishing process

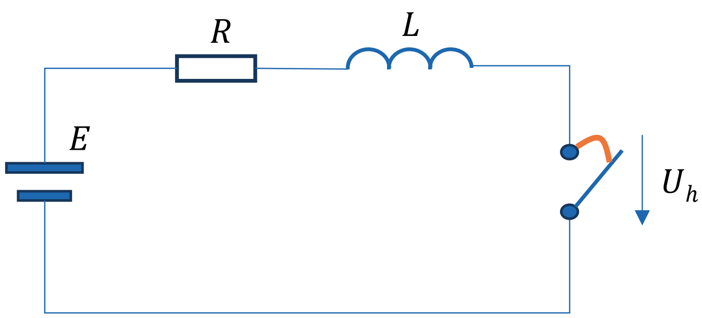


Fig.2 Arc in DC circuit

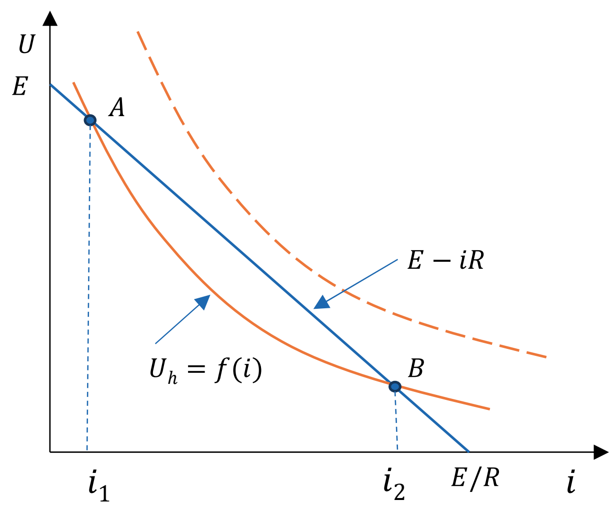


Fig.3 Analysis of the characteristics of DC arc

From a circuit perspective, a DC arc is a nonlinear resistor whose resistance value varies with the current and other factors. The voltage balance equation of the circuit after arcing can be written as equation:

(1)

$$E = iR + L\frac{di}{dt} + U_h$$

(2)

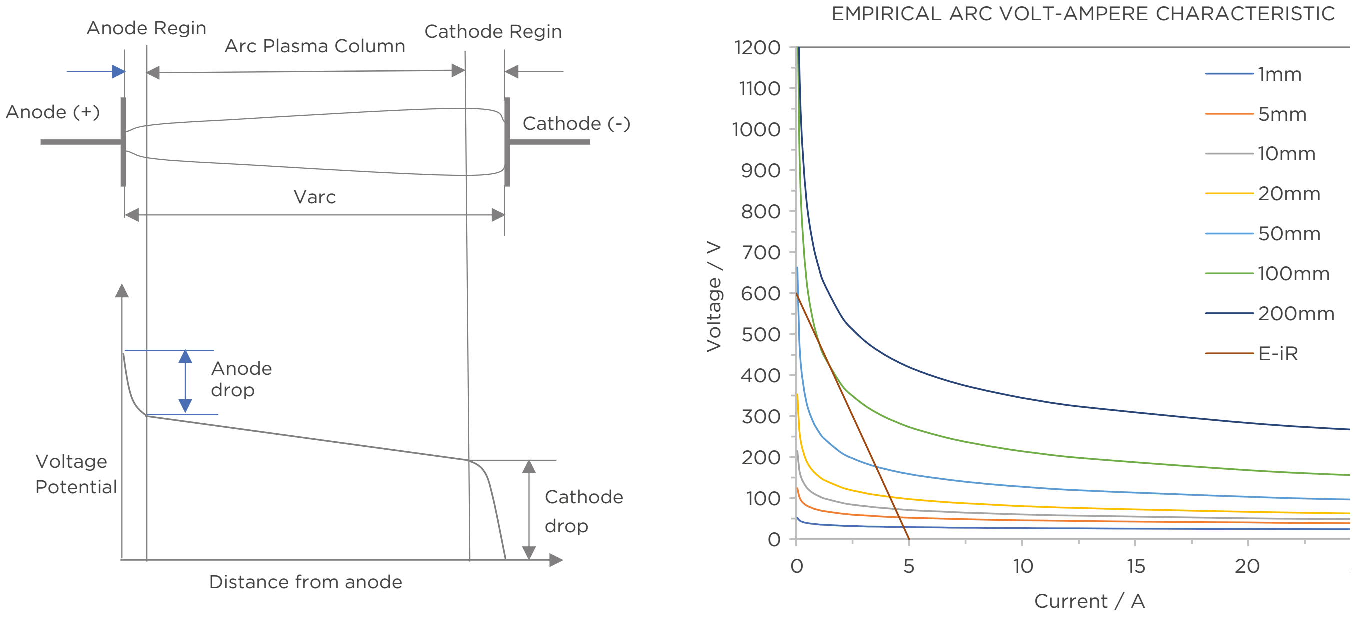
$$U_h = f(i)$$

In Figure 3, the arc Volt Ampere curve **Uh** intersects with **E-iR** at points **A** and **B**, where point **B** is referred to as the stable combustion point.

The arc extinguishes, when the static volt ampere characteristic of the arc is increased to the point where **Uh** no longer intersect with the **E-iR** curve, then:

$$E - iR < Uh \quad (3)$$

Equation 3 states that when the power supply voltage is insufficient to balance the combination of the arcing voltage and the voltage drop of the circuit resistance, then the arcing current decrease until the arc extinguishes. Therefore, increasing the arcing voltage contributes to extinguishing the arc.



(a) Electric arc characterization

(b) Volt-Ampere characterization of DC arc

Fig. 4 Electric arc characterization between copper electrodes in air

As show in figure 4.(a), The arc consists of three regions: the anode region, the arc plasma column, and the cathode region. Research in the field has discovered that the total voltage drop in the anode and cathode regions mainly depends on the material of the electrodes. For example, the voltage drop of a copper electrode is about 23.5V, while the voltage drop of the arc plasma column varies as a function of the arcing current.

According to reference [2] the Volt-Ampere characterization of a free burning arc in air can be calculated and is shown for different electrode distances (contact gap) in the chart of Figure 4. (b). This chart indicates that a large contact gap is needed to extinguish a high current and high voltage arc in air. For example, in a circuit with a voltage of 600Vdc and a current of 5A, the curve E-iR lies just below and comes closed to the Volt-Ampere curve of arc at an electrode gap of 100mm. As a result, a contactor switching a load of 600Vdc and 5A requires a contact gap of at least 100mm to extinguish the arc reliably. However, a contact gap of 100mm is too large for typical applications since the contact gap is proportional to the size of the contactor. Typical DC contactors are designed with much smaller contact gaps of around 1.5mm–4mm. Therefore, certain methods must be applied in DC contactors to increase the arcing voltage to a maximum to ultimately extinguish the arc within the available space.

The following methods are known to increase the arcing voltage:

- increase the length of the arc and reduce its diameter
- divide the arc into multiple segments and increase the arcing voltage by utilizing the voltage drop in the anode and cathode regions
- cooling the arc

These methods are utilized the following way in DC contactors comprising of two fixed contacts, a movable contact bridge, and arc blowing permanent magnets in a sealed, gas filled, contact chamber.

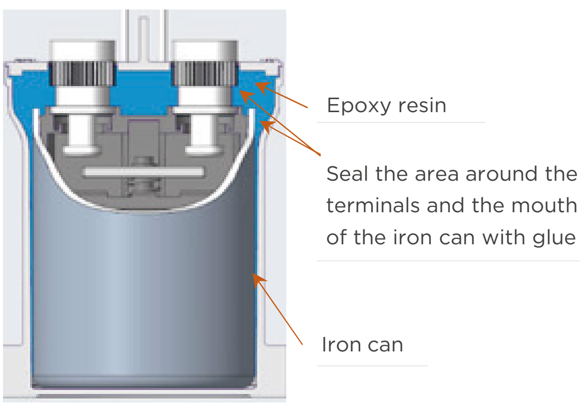
First, while breaking the load the arc is divided into two sections between the two sets of contacts as the movable and stationary contacts separately. Next, the arc is stretched as the distance between the contacts increases. Then, the arc moves away from the contact area under the influence of the arc blowing magnetic field and further elongates in the arc chamber. In addition, the high-pressured gas inside the arc chamber cools the arc until it finally extinguishes.

3. Sealed DC contactor with gas filling

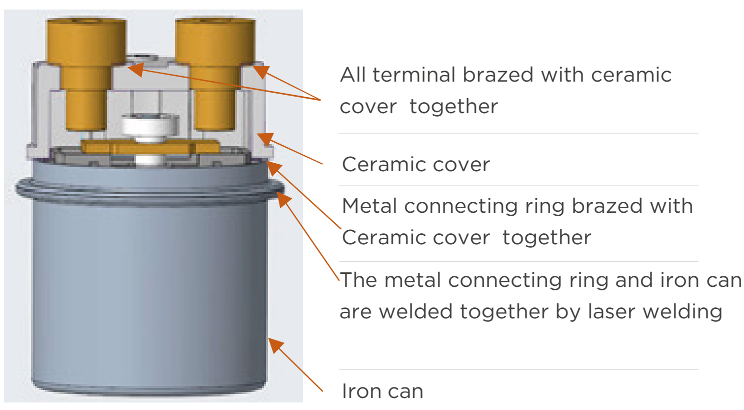
	Nitrogen	Hydrogen
Atomic weight(u)	14.007	1.008
Gas molecule diameter (nm)	0.364	0.289
Thermal conductivity (W/mK)	0.02583	0.1805
ionization energy (Kj/mol)	1402.3	1312
Dielectric strength (kV/cm)	33	15

Fig. 5 Physical Characteristics of hydrogen and nitrogen

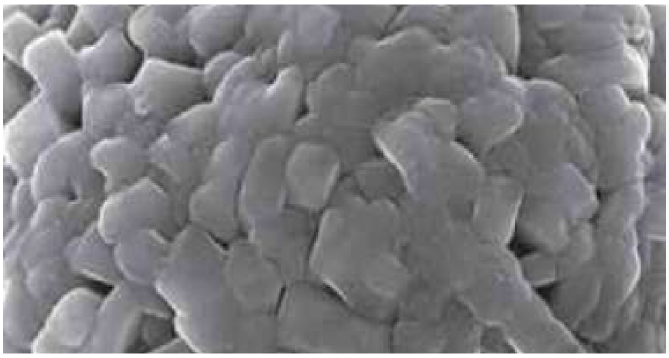
A comparison of the thermal conductivity of hydrogen compared to nitrogen shows that it is about 7 times higher. As a result, an arc can be cooled faster in hydrogen than in nitrogen. Further, the atomic mass of hydrogen is smaller than nitrogen, thus the arc can move faster and elongate more in hydrogen, under the influence of the arc blowing magnetic field. Therefore, hydrogen can extinguish an arc at higher voltages and currents. In terms of size, hydrogen molecules are smaller than nitrogen molecules and are therefore more prone to leakage.



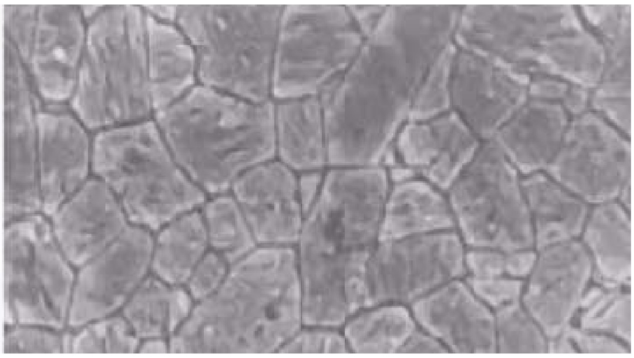
(a) Epoxy sealing structure



(b) Ceramic sealing structure



(c) crystal structure – epoxy



(d) crystal structure – ceramic

Fig.6 Epoxy, ceramic sealing diagram and crystal structure between epoxy and ceramic

Presently, gas filled and sealed DC contactors mostly rely on two types of sealing which are illustrated in figure 6. (a) and (b). They consist of either iron cans with epoxy resin sealing or metal shells with ceramic brazing and laser welded sealing. The crystal structure of ceramic material has a higher density compared to epoxy resin sealing, see figure 6. (c) and (d). This leads to a much lower permeability of gas through ceramic than through epoxy resin and is the reason why ceramic-based sealing is beneficial and necessary for hydrogen filled contactors.

Generally, due to the requirements of dielectric strength, influence of gas leakage, and arc extinguishing performance, the pressure of hydrogen filling is higher than that of nitrogen filling.

	H2	N2
Epoxy	1.07×10^{-10}	2.7×10^{-11}

Unit: cm^3 (STP)·cm/(cm^2·s·Pa)

$$Q = \frac{\rho \cdot A \cdot t \cdot (p_1 - p_2)}{l} \quad (4)$$

Q: Gas leakage volume [cm^3 (STP)]

ρ : Permeability

A: Surface area (cm^3)

t: Time (s)

$p_1 - p_2$: Pressure difference (Pa)

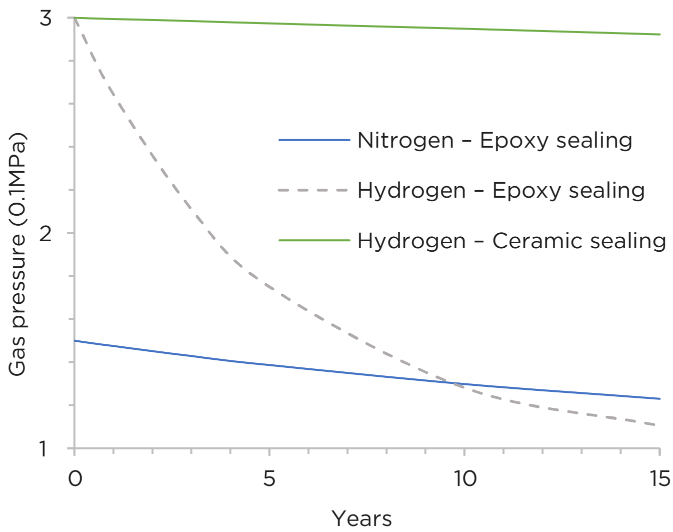
Permeability of hydrogen to ceramic and iron material

Al_2O_3 Ceramic	1.2×10^{-24}
Iron	1.38×10^{-24}

Unit: cm^3 (STP)·cm/(cm^3·s·$Pa^{0.5}$)

Reference [3][4][5]

(a) Gas permeability to epoxy and related formula.



(b) Calculated gas pressure over time

Fig.7 Permeability and gas pressure over time comparison

The pressure of the gas inside the contact chamber has a significant impact on the arc extinguishing ability of the contactor when separating high voltage and high current. If the pressure inside the contact chamber is too low, then the contactor loses its ability to extinguish the electric arc. This can lead to a destruction of the contactor or even an explosion or fire.

As shown in Figure 7, the permeability of hydrogen gas through ceramics is much lower than that through epoxy adhesive. According to formula (4), the pressure of ceramic sealed contactors filled with hydrogen remains at a relatively high level even after almost 15 years whereas the pressure of epoxy sealed contactors filled with hydrogen reduces to nearly the ambient pressure within the same timeframe. This clearly underlines the need for ceramic based sealing in combination with hydrogen fillings.

4. Comparison of Arc in hydrogen and nitrogen

4.1 Analysis of arc characteristics during DC breaking process

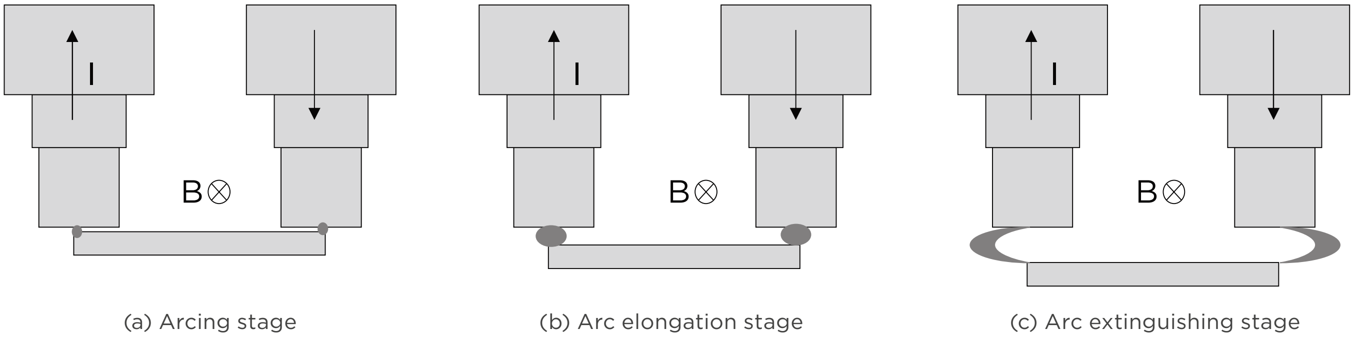


Fig. 8 Status of contact and arc

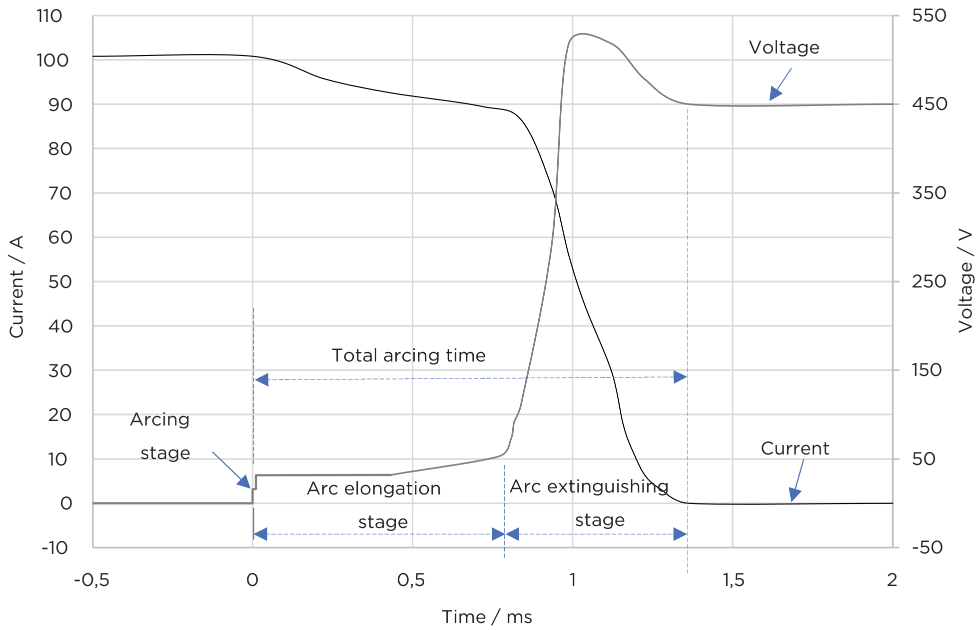


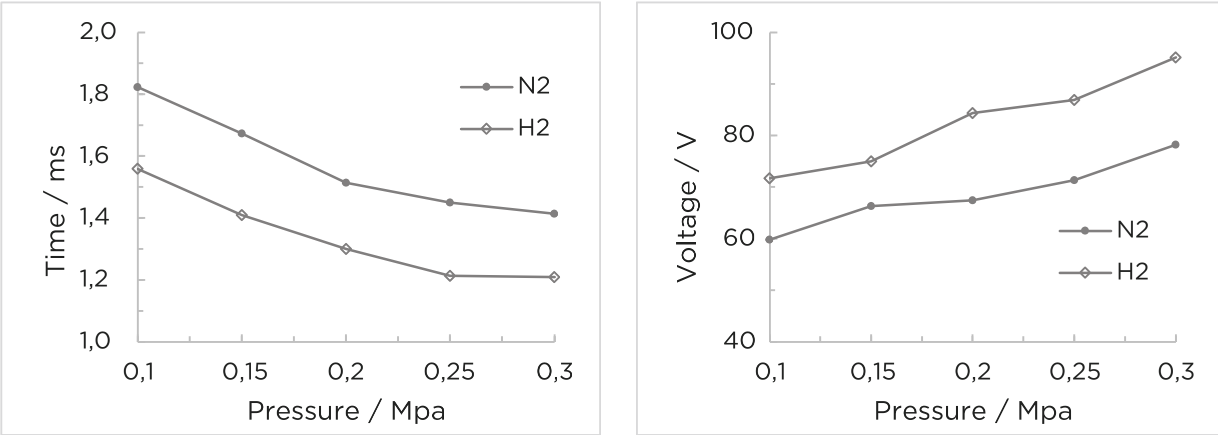
Fig.9 DC arc voltage and current waveform during DC circuit breaking process.

According to reference [1], the arcing process can be divided into three stages: the first stage is the arcing stage which begins when the movable and stationary contacts are separated, as shown in Figure 8 (a). In this stage, an arc is generated between the contacts and corresponds to the time t=0ms in Figure 9, a step can be identified in the voltage curve, and the voltage approaches the value of the anode and cathode voltage drop of both electrodes, of about 30V.

In the second stage the arc burns and gradually elongates between the movable and stationary contacts, as shown in figure 8 (b). During this stage, the length of the arc is equivalent to the distance between the separated contacts, which is relatively small. The strength of the electric field between the contacts is high, and the magnetic blowing force cannot blow the arc away from the contact area. The arcing voltage slowly increases as the distance between the separating contacts increases.

In the third stage the arc is elongated rapidly until it extinguishes, as shown in Figure 8. (c). When the distance between the movable and stationary contacts increases to a certain value, the electric field strength decreases, and the arc is blown out of the contact area under the influence of the magnetic blowing force through which the arc elongates rapidly. The arcing voltage increases rapidly and exceeds the system voltage. A higher arcing voltage helps offset the system voltage, causing the current to reach zero and the arc to extinguish.

4.2 The influence of gas medium on the characteristics of arc breaking.



(a) Arcing time (b) Arc voltage at 0.8mm gap

Fig.10 Arc time under different pressures.

In reference [1], the author compared and analyzed the effect of gas media on the characteristics of multiple interrupting arcs by filling experimental samples with different media such as hydrogen and nitrogen. Figure 10 shows the arcing time of nitrogen and hydrogen at gas pressures ranging from 0.1Mpa to 0.3Mpa. And the arc voltage when the contact gap reaches 0.8mm, at this point, the arc is completely located between the contacts, in a slow elongation stage, and the arc voltage is relatively stable. As shown in Figure 8, under the same conditions hydrogen leads to shorter arcing times and higher arc voltage compared to nitrogen.

Increasing the pressure can significantly shorten the arcing time and increase the arcing voltage. However, it can be seen in Figure 10 that the relative increase in performance begins to flatten at pressures beyond 0.2Mpa. Therefore, a pressure beyond 0.2Mpa does not significantly contribute to increasing the performance. In fact, excessive pressure will increase the difficulty of sealing the device and the impact on contact erosion will become more complex.

TE compared the arcing time of samples filled with hydrogen at 0.3Mpa and nitrogen at 0.15Mpa for 10 consecutive switching cycles at 100A and 450Vdc resistive loads in identical products. The results showed that the arcing time of samples filled with hydrogen was much smaller than that of samples filled with nitrogen.

Under the conditions of switching a 750Vdc and 100A resistive load, the nitrogen filled test samples could no longer extinguish an arc after a few switching cycles, while the hydrogen filled test sample was able to switch normally and did not fail, even after almost 1000 cycles. This shows that DC contactors filled with hydrogen gas can extinguish arcs of higher DC voltages than ones filled with nitrogen gas.

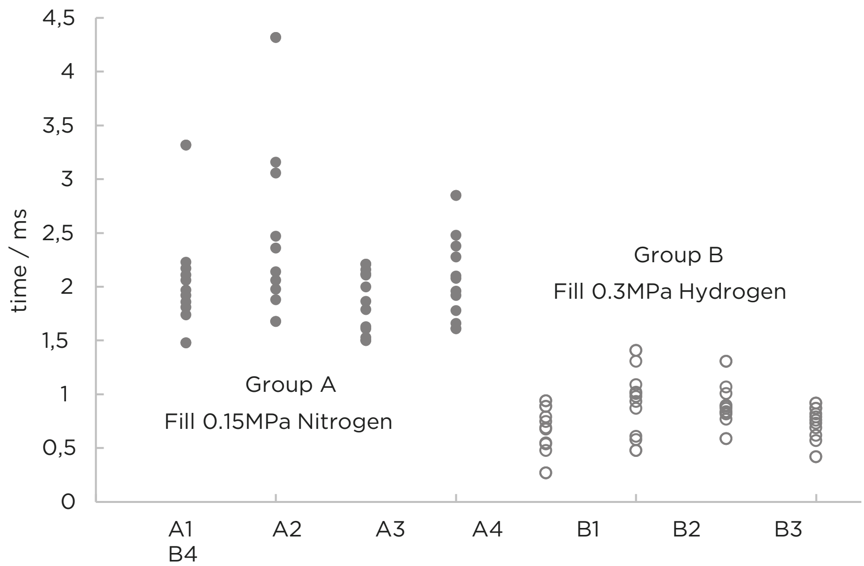


Fig.11 Arc time comparison between nitrogen and hydrogen filling

4.3 Dielectric strength comparison between nitrogen and hydrogen filling

Under standard conditions, the dielectric strength of nitrogen is approximately twice that of hydrogen. According to Paschen's law, the breakdown voltage (**V**) of a gas is a function of the product of gas pressure (**p**) and distance (contact gap **d**):

$$V = f(pd) \tag{5}$$

The following figure shows the Paschen curve of breakdown voltage for nitrogen and hydrogen gas.

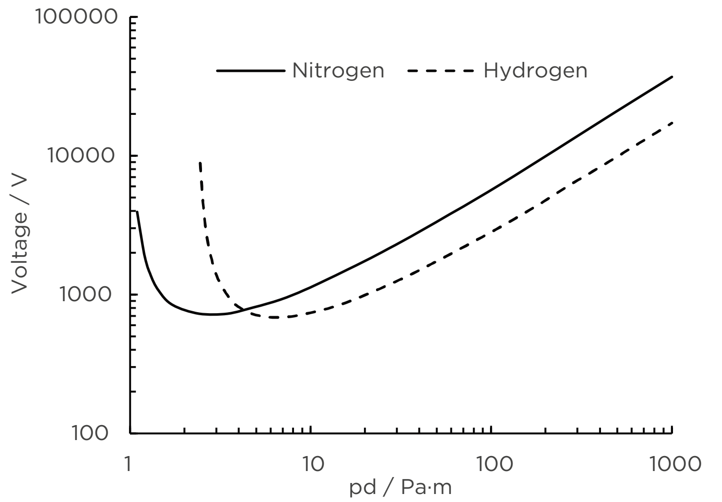


Fig.12 Paschen's curves of hydrogen and nitrogen

Under the same conditions, the dielectric strength of hydrogen is lower than that of nitrogen. As the pressure of the gas filling increases, the insulation performance of the gas also rises.

The total distance between the contacts of the experimental samples used for comparison is about 3.2mm. hydrogen gas with a pressure of 0.3MPa and nitrogen gas with a pressure of 0.15Mpa are filled separately to measure the breakdown voltage between the contacts. The data shows that the average breakdown voltage of samples filled with 0.15Mpa nitrogen gas is 17% higher than that of samples filled with 0.3Mpa hydrogen gas.

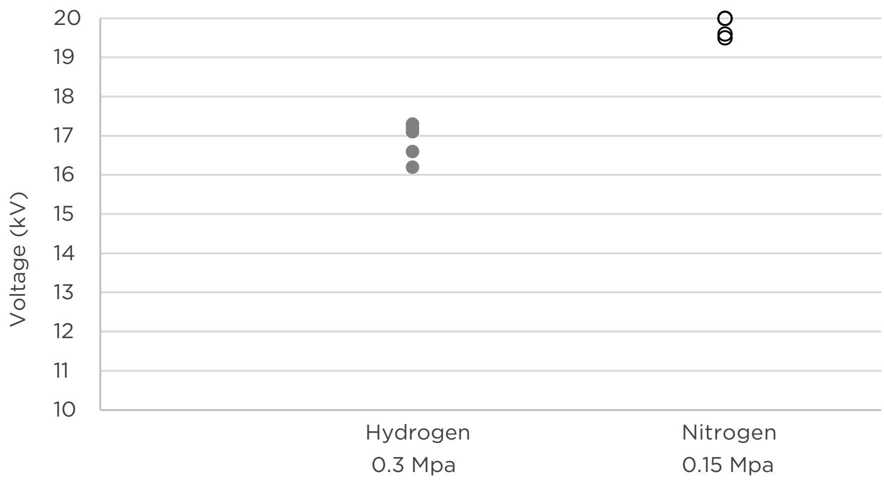


Fig.13 Dielectric strength comparison between nitrogen and hydrogen filling

5. Conclusion

1) Due to its high thermal conductivity, small molecular weight, and low density, hydrogen has excellent arc extinguishing performance. At the same pressure, the arc ignition time is shorter in hydrogen than in nitrogen, and the arcing voltage, which is necessary for extinguishing the arc, rises faster in hydrogen.

2) Increasing the pressure of hydrogen and nitrogen fillings can significantly improve the breaking performance. However, when the pressure exceeds 0.2Mpa, the relative performance improvement begins to flatten and does not increase significantly onwards.

3) Hydrogen gas fillings can extinguish arcs of higher DC voltages compared to nitrogen gas fillings.

4) The pressure of the gas filling will affect the insulation breakdown voltage of the contact. Under the same contact gap conditions, and when the pressure of hydrogen gas is twice that of nitrogen gas, the insulation breakdown voltage of the contact of hydrogen gas filled products is slightly lower than that of nitrogen gas filled products by about 17%. The lower insulation performance of hydrogen compared to nitrogen can lead to arc reignition after initially extinguishing the arc under certain load conditions. Arc reignition can effectively be prevented by filling DC contactors with a mixture of hydrogen and nitrogen. However, further research is needed on gas mixtures of hydrogen and nitrogen.

5) The permeability of hydrogen to ceramics is very low, and after more than a decade of hydrogen filling in ceramic seals, the internal pressure can also be maintained at a relatively high level. ceramic sealing requires the use of metallization treatment at each connection of ceramics, reliable sealing welding with other metal parts using brazing technology, and laser welding technology. The entire production process is complex and requires strict control, which makes the product cost relatively high compared to products sealed with epoxy.

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