ARC DISCHARGE ENERGY GENERATED BY AN ELECTRICAL SHORT IN THE COIL WINDING OF A COMPRESSOR IN A ROOM AIR CONDITIONER POWERED BY AN INVERTER POWER SOURCE

○Tomohiko IMAMURA*, Masato TAKAGI, Shugo AIDA*, Ryosei HIRANO*, and Jun-ichi SUEMATSU**

*Dept. Mechanical and Electrical Engineering, Suwa University of Science, Chino-shi, Nagano, 391-0292, Japan

**Graduate School of Engineering and Management, Suwa University of Science, Chino-shi, Nagano, 391-0292, Japan

ABSTRACT

A series of investigations have been conducted to quantify the discharge energy generated by electrical short circuits of the coil winding inside the compressor of an AC200V inverter-driven commercial room air conditioner. An experimental setup and a numerical simulation model were developed to reproduce critical environment of 6 MPa and 150 °C. The luminescence due to the discharge increased with rising pressure and temperature, while the discharge duration was conversely shortened. The discharge energy generated by phase-to-phase short circuits of the coil winding was at most 5-7 mJ, regardless of the ambient pressure and temperature. These energies were reproduced by theoretical estimations based on gas temperatures derived from spectroscopy analysis. Furthermore, they also showed good agreement with the results obtained from numerical simulations. These findings suggest that the discharge energy generated by electrical short circuits inside the compressor of an inverter-driven AC 200V commercial room air conditioner can be reliably estimated.

Keywords: Arc discharge, Coil winding, Phase-to-phase electric short, Compressor, low-GWP refrigerant

INTRODUCTION

Replacing current refrigerants with low-GWP (global warming potential) gases such as hydrofluoroolefins (HFOs), hydrocarbons (HCs), or their blends has attracted attention as a means to achieve carbon neutrality. However, some of these gases exhibit varying degrees of flammability and/or self-decomposition. In particular, self-decomposition reactions can cause greater pressure rise and more severe damage even in the absence of oxygen; therefore, risk assessment of whether such reactions can occur in commercial equipment is indispensable. Self-decomposition reactions are triggered when an energy source exceeding the critical energy is introduced under critical pressure and temperature conditions. Thus, quantitative identification of possible energy sources in accident scenarios is the key requirement. The most likely energy source is considered to be discharges generated by electrical shorts in the coil windings or terminals of a compressor. Based on this background, the present study aims to quantify the discharge energy generated by electrical short circuits between different phases of the coil windings in the compressor of an inverter-driven commercial room air conditioner, under various temperature and pressure conditions, using both experimental and numerical approaches.

PROCEDURES

EXPERIMENTAL

Fig. 1 shows a schematic of experimental setup. A commercial room air conditioner unit (AC 200V, single phase, rated power: 3.6 kW for cooling and 4.0 kW for heating, compressor power: 0.56 kW) was used. The power cables between the inverter-driven power source and the compressor were split, and two of them were connected to the ends of electrodes in the chamber, as shown in Fig. 2. The chamber (volume: 1.5 L, pressure resistance: 6 MPa) was made of SUS316 stainless steel. A pair of electrodes was mounted horizontally in the chamber. One electrode, made of copper and serving as the cathode, was fixed, while the other, made of SUS316 stainless steel and serving as the anode, was movable by controlling the rotation of a stepping motor. By bringing these electrodes into contact, electrical short circuits under actual compressor operating conditions could be reproduced. Both electrodes had a diameter of 6.2 mm. The refrigerant temperature inside the chamber could be

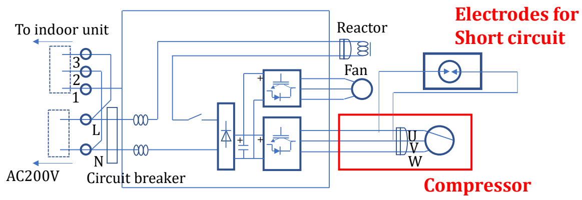

Fig. 1 Schematic of experimental setup.

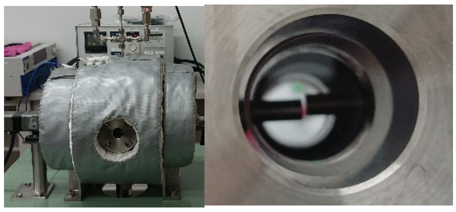

Fig. 2 Photo of test chamber (left) and electrode (right)

controlled up to 150 °C using a jacket heater that covered the entire chamber.

The voltage across the electrode pair and the short-circuit current were measured using a differential high-voltage probe (Tektronix, P5200A) and current probe (HIOKI, CT6873), respectively. The visible discharge at the electrode gap was captured by a high-speed camera (NAC MEMRECAM ACS-1 M60). An optical fiber connected to a spectrometer (OPAL-Luxe, Hamamatsu Photonics) was placed at the center of the observation window.

Air and nitrogen were used as ambient gases at room temperature. The ambient pressure was varied from 0.1 to 6.0 MPa. For the nitrogen tests, additional experiments were conducted at an ambient temperature of 150 °C, with pressures of 1.0, 2.0, 3.0 and 4.0 MPa. Each short-circuit test was repeated at least 10 times for each combination of ambient gas, temperature, and pressure.

NUMERICAL SIMULATION

A numerical simulation to reproduce an arc discharge at the electrode gap was conducted using VizSpark (version 2.4.4). A two-dimensional simulation domain with a width of 3 μm and a height of 6 μm, as shown in Fig. 3(a), was developed. The electrode closing speed was set to 200 mm/s to simulate sudden closing. The short-circuit model consisted of a constant-voltage DC 250 V power supply, a resistor to limit the current to 70 A, and electrodes, as shown in Fig. 3(b). The initial temperature was fixed at 300 K, while the initial pressure was varied across three cases: 0.1 MPa, 10 MPa, and 1.0-7.0 MPa in 1.0 MPa increments.

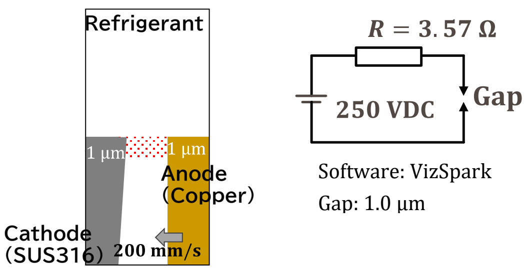

Fig. 3 Schematic of (a) simulation domain and (b) equivalent circuit.

RESULTS

DEPENDENCES OF ARC CHARACTERISTICS ON AMBIENT PRESSURES AND TEMPERATURES

Fig. 4 shows typical voltage and current profiles before and after an arc discharge caused by an electrical short between V-W phases of a compressor. Immediately after the short circuit, the voltage dropped while the current increased. The voltage remained at approximately 20 V until 0.012 ms after the short circuit, but the current continuously decreased over time, then exhibited high-frequency fluctuation, and finally dropped to zero. The arc discharge voltages for copper and SUS316 electrodes have been reported approximately 20 and 30 V, respectively [3,4]. Thus, the present arc discharge data are considered reasonable.

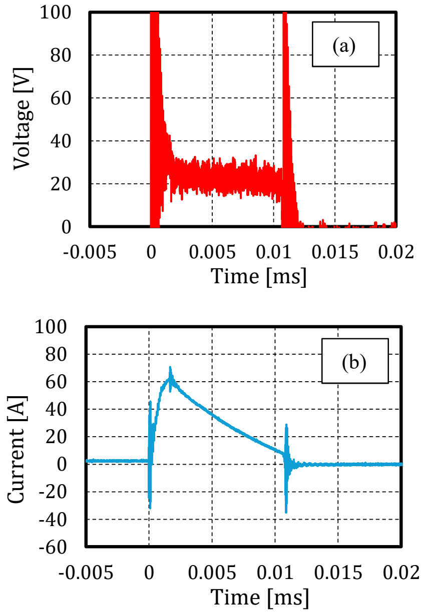

Fig. 4 Typical profiles of (a)voltage and (b)current in V-W phases electrical short circuit. Pressure: atmospheric, Temperature: room temperature.

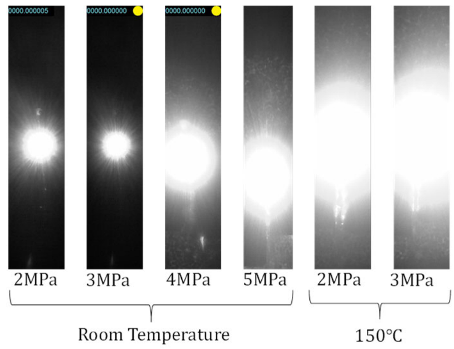

Fig. 5 Photos of luminescence of spark generated by electric short circuit under various pressure and temperature.

Fig. 5 shows photographs of discharge plasma at its maximum size under each condition. The strongest luminescence was observed within 5 μs after initiation of discharge in all test cases. It was also observed that the bright region expanded with increasing ambient pressure and temperature, with temperature having the greater influences. In contrast, the sustained duration of luminescence became shorter with increasing ambient pressure, whereas it was extended by increasing ambient temperature.

The increasing in discharge luminescence originates from the higher frequency of collisions between electrons and molecules. The collision frequency naturally increases with increasing ambient pressure. Furthermore, the mean free path of electrons and molecules increases with rising temperature. Therefore, the region of discharge luminescence expands under higher pressure and temperature conditions.

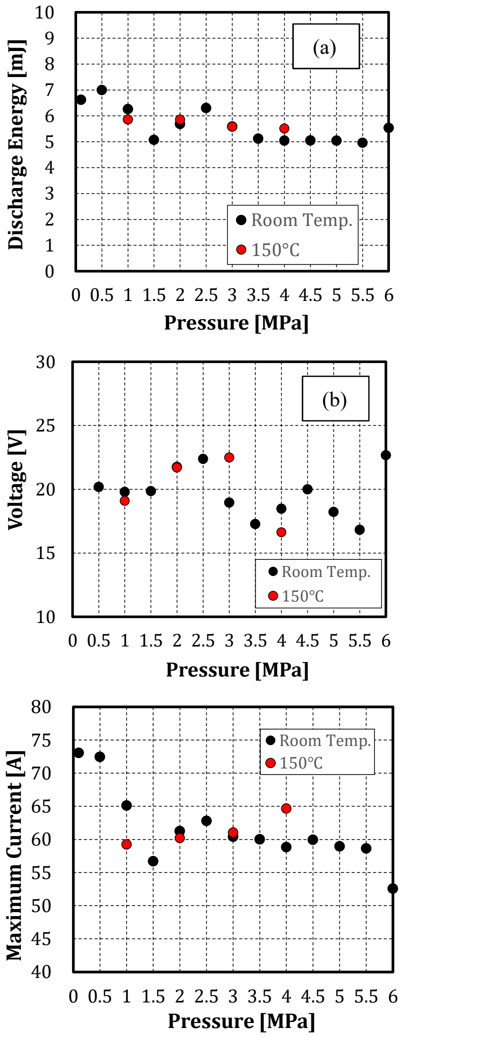

Fig. 6 Dependences of (a)discharge energy, (b)voltage, (c)maximum current on pressure.

Fig. 6 shows the dependence of discharge energy, arc current, and arc voltage on the ambient pressure. The discharging energy slightly decreased with increasing ambient pressure due to the shortened duration of discharge. A similar trend—that the duration of discharge decreases with increasing ambient pressure— has also been reported by other researchers [2]. Under the present experimental conditions, the discharge energy was at most 7 mJ. The arc current decreased with increasing pressure, whereas the arc voltage showed little variation. It is considered that the arc voltage is determined by thermionic emission characteristics, which are governed by the electrode materials. Therefore, ambient gas conditions such as pressure, temperature, and thermal properties, have little influence on arc voltage. In contrast, the arc current is determined by electron motion and thus depends on these ambient conditions.

However, the expansion of the luminescence region with increasing pressure and temperature, as shown in Fig. 5, appears to contradict the results for discharge energy. Therefore, the energy stored in the plasma was estimated using the Boltmann plot method. The parameters required for this estimation were obtained from spectroscopic analysis. A gas temperature of 10^2–10^3 K was obtained, and the stored energy corresponding to this temperature was estimated as 1.7-5.6 mJ, assuming that only the core of the luminous region—approximately 1 mm in diameter—reaches the high gas temperature. These estimated energies were generally in good agreement with the discharge energies obtained from the current and voltage waveforms.

REPRODUCE OF ARC DISCHARGE BY NUMERICAL SIMULATION

Fig. 7 shows profiles of voltage and current under three conditions of ambient pressure obtained by the numerical simulation. The sharp change in current and voltage is considered to correspond the breakdown event and in the stage of glow discharge, after which the discharge is assumed to transition into arc discharge. It was confirmed that the timing of the breakdown event varied depending on the initial pressure.

Figs. 8 show contour maps of calculated temperature and current density at t = 0.2 μs and 0.6 μs after breakdown under 0.1 MPa of ambient pressure, respectively. From Fig. 8(a), it can be observed that glow discharge occurs across the entire electrode surface, leading to producing uniform distribution of temperature. In contrast, as shown in Fig. 8(b), the discharge path becomes more concentrated and an arc discharge occurs. As a result, current is locally concentrated, and the temperature near the electrodes appears to decrease.

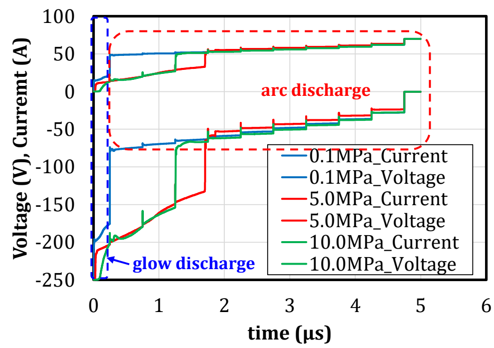

Fig. 7 Typical profiles of voltage and current generated by electric short circuit obtained by the numerical simulation.

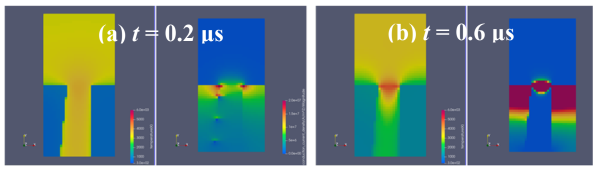

Fig. 8 Contour maps of temperature (left) and current density (right) at atmospheric pressure. t: time since breakdown

Fig. 9 shows the calculated discharge energy with pressure. The energy only in arc discharge shows downward convex curve which takes minimum energy at 5.0 MPa. However, the energy which estimated whole glow and arc discharging process shows linear dependence in slightly downward to the right, and its trend is good agreement in the experimental results. Furthermore, although the absolute value of calculated energy was approximately double to that of experimental data, the order of them was in good agreement. Therefore, the discharge energy due to the electric short between the difference phases of the coil windings of the compressor in commercial room air conditioner can be estimated by the present simulation method.

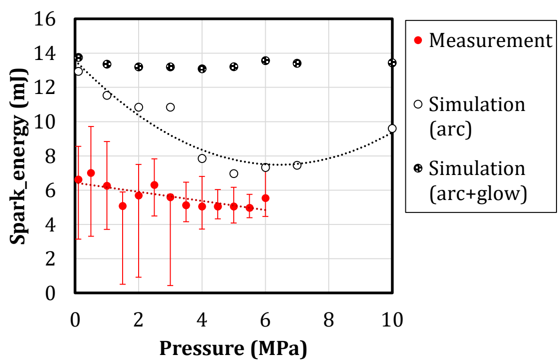

Fig. 9 Comparison of the relationship between spark energy and pressure of experimental results with numerical simulation.

CONCLUSIONS

In this study, a quantitative investigation on the arc discharge characteristics generated by electrical short circuits of the coil windings in the compressor of an inverter-driven AC 200 V room air conditioner was carried out. No significant differences were observed in the voltage and current profiles regardless of short phases. The discharge energy was at most 7 mJ. The arc current significantly decreased with increasing ambient pressure. Although the plasma luminescence expanded with increasing pressure and temperature, the duration of discharge was shortened. The discharge energy estimated from gas temperature, obtained through spectroscopic analysis, was in good agreement with the experimental results. Furthermore, a numerical simulation method was developed to estimate the discharge energy caused by electrical short circuits, and the results also showed good agreement with the experimental data.

ACKNOWLEDGEMENTS

This work is part of the ongoing research conducted since FY2023 under the project "Development of High-Efficiency Refrigeration and Air Conditioning Technologies for Practical Use of Next-Generation Low-GWP Refrigerants" (Project No. JPNP23001), supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

REFERENCES

[1] F.G. Keyes and R.B. Brownlee : J. Am. Chem. Soc., **40**(1), 25(1918).
[2] R. Tillner-Roth et al. : "Thermodynamic Properties of Pure and Blended Hydrofluorocarbon (HFC) Refrigerants", JSRAE, (1997).
[3] R.Henmi, Y.Yokomizu, T.Matsumura, Anode-fall Voltages of Air Arcs Between Electrodes of Copper, Silver and Tungsten at Currents up to 1500 A, IEEJ Trans. PE, 124(1), 143-149, 2004.
[4] American Iron and Steel Institute, Welding of Stainless Steels and Other Joining Methods, A Designers Handbook Series N9002, 1988.