Experimental Investigations Into Low Current Steady State Arcs In A Dual-Airflow Model Interrupter

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Abstracts

It is well-known that shock waves frequently occur inside the nozzle of the interrupter, and that they play important roles in the arc interruption.

A model interrupter with two-dimensional dual-airflow nozzles was used for this experiment. The arc was ignited with 1.4 mil copper wire stretched between the electrodes which were spaced out 56 mm. The arc current of 60 to 230 A was achieved by adjusting the external resistance from 5.5 to 1.6 ohms. The arc tests have been conducted for investigating the air arc characteristics, and the effects of shock waves and nozzle pressure ratios on the arc voltage, the arc resistance, the arc power, and average electric field. The results of these tests have been analyzed to provide insights into the arc characteristics for gas circuit breakers.

The average electric field is represented by the function of the arc current to show the negative E-I characteristic explicitly. The effects of shock waves and nozzle pressure ratios are shown to be significant for a circuit breaker performance.

1. Introduction

It has been demonstrated that shock waves frequently occur inside the nozzle of the interrupter, and that they play important roles in the arc interruption.

Previous investigations have been primarily concentrated on the existence of shock waves in the nozzle[1,2], on the variations in pressure, density, velocity and temperature caused by shock waves[1,3] and on the sudden changes in the luminosity of the arc column produced by shock waves which appeared in Schlieren photographs and high-speed movie pictures[3,4]. There have also been recent experimental attempts to investigate the effects of shock waves on arc characteristics[5,6,7]. But the investigations have been restricted to the location of shock waves in the nozzle, and the effects of shock waves on the arc voltage and power. These experiments were performed exclusively at the arc current range of 45 to 110 A in order to analyze dc arcs in two-dimensional, three-dimensional, and orifice nozzles.

In this research, on the other hand, the effects of shock waves and nozzle pressure ratios on the arc voltage, average electric field, arc resistance and arc power will be investigated in a two-dimensional nozzle with an arc current range of 60 to 230 A.

2. Experimental Apparatus

2.1 Interrupter

The model interrupter used in these experiments is of the two-pressure, dual-flow type, which can be instrumented to obtain cold flow and arc properties. Fig.1 shows a schematic of a dual-flow interrupter. Two nozzles are mounted in the center section. These nozzles are identical except that one is constructed with a fiberglass mounting base, a glass supporter and a copper nozzle for optical observation, while the other is made entirely of copper.

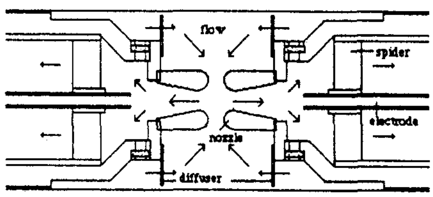

Fig.1. A schematic of a dual-flow interrupter.

The flow of gas is admitted through four large windows mounted in the nozzle section of the interrupter. These windows also permit optical observa-tion, serve as inlet ports for the pressure probes, and are large enough to provide service access for replacement and repair of the nozzles. After the flow of gas has entered the inlet and passed through the throat and exit of the nozzles, it streams through a pipe of 10.16 cm in diameter to a tank evacuated by vacuum pumps.

2.2 The Flow System

Fig.2 contains a block diagram of the flow system. After the gas has passed through the nozzle assembly it discharges into a low pressure dump tank of 56.6 m^3 capacity. A bank of five vacuum pumps evacuates the dump tank and maintains a constant low pressure at the nozzle exit for a test duration of approximately 30 seconds, allowing for test runs at approximately 20 minute intervals. For these experiments, atmospheric air provided the high pressure upstream of the nozzle, while the pressure downstream of the nozzle varied. The upstream to downstream pressure ratio was varied by changing the opening of the control valve, thereby controlling the flow speed through the nozzles.

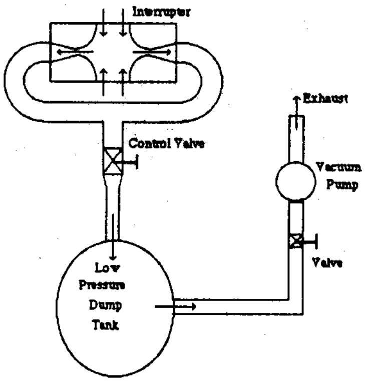

Fig.2. A block diagram of the flow system.

2.3 Two-dimensional Dual-flow Nozzles

Two identical dual-flow nozzles were constructed to accelerate the flow between the upstream region at atmospheric pressure and the downstream region at a variable low pressure. One of the nozzles was constructed with a rectangular mounting flange of 0.635 cm thick plexiglass, a side wall of 0.635 cm thick glass, a diverging section made of brass and a converging cap section made of copper, as shown in Fig.3.

The converging section of the nozzle was designed with curvature radii of 0.873 cm and 0.556 cm respectively, a thickness of 0.635 cm, an outside diameter of 5.08 cm, and a throat diameter of 1.27 cm. The diverging section of the nozzle was designed with a thickness of 1.27 cm, a total length of 3.81 cm and a divergence angle of 15.9° . The converging cap section functioned to establish a smooth flow of gas, i.e., to smooth the transition from a converging three-dimensional flow to a diverging two-dimensional flow.

This feature of the nozzle caused a slight discontinuity in its geometry, however, because the cross-section area at the nozzle throat transformed a circular shape with a radius of 0.635 cm into a square section with a length of 1.27 cm. A schematic of the nozzle with its dimension is shown in Fig.3.

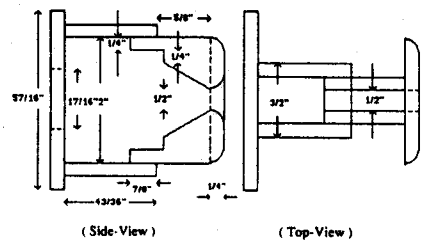

Fig.3. A schematic of the nozzle and its dimensions.

2.4 Electrodes

Each electrode consisted of an electrode copper tube of 0.635 cm outer diameter, an electrode copper-tungsten(70% Cu) tip 2.54 cm in length with a 0.635 cm diameter, and a plastic insulator 11.43 cm in length. Fig.4 shows a schematic of the electrode. The arc chamber protruded on both sides, creating sockets for the two electrodes. The plastic insulators on the electrodes were threaded and screwed into the test section. Using a lathe, a hole with a diameter of 0.127 cm was slowly drilled on the centerline of the electrode. A copper ignition wire, 1.4 mil thick, was strung through these holes and stretched between the electrodes in order to ignite the arc when voltage was applied.

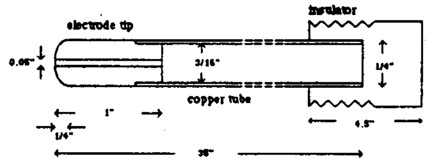

Fig.4. Schematic of the electrode.

3. The Arc Test Circuit and Experimental Procedures

3.1 The Electric Arc Test Circuit

The test circuit for this experiment is shown in Fig.5. The main power supply(Vs) was three phase 480 Vac. The circuit breakers(CBa and CBb; rated at three phase 600 Vac 150 HP) were for closing the test circuit. The main power supply was protected by fuses, rated at 600 Vac 125 A class RK5, installed in the CBb enclosure.

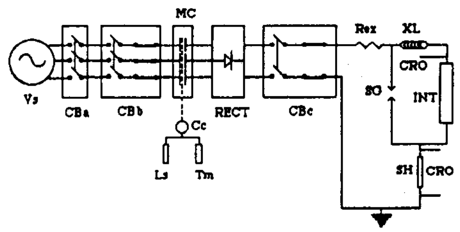

Fig.5. The electric arc test circuit.

A magnetic contactor(MC), rated at three phase 600 Vac 100 HP, opened and closed the test circuit. The opening circuit of this contactor was energized by another 110 Vac power supply, and was connected in series with a timer(10 A, 120 Vac, adjustable time delay interval of 0.1 to 1 second) embedded in the MC enclosure. The closing circuit was controlled by the 10 Vdc signal of a sequential timer. This 10 Vdc signal energized the coil of the solid state relay, the contact of which was connected in series with the MC closing coil(Cc) through the limit switch(Ls) of the gate, which was electrically interlocked with the magnetic contactor. The duration of the test could be varied by the sequential timer and the timer(Tm) embedded in the MC enclosure.

The rectifier(RECT) converted the available 480 Vac into 640 Vdc to obtain a low voltage dc arc. The rectifier was protected by the fuses(rated at 600 Vdc, 125 A, dual element, time delay, class K5) installed in the CBc enclosure. The typical output voltage of the rectifier fluctuated between 780 Vmax. and 600 Vmin. to yield an amplitude of approximately 690 Vrms. The circuit breaker CBc, rated at single phase 600 Vdc 50 HP, was for making the test circuit closed.

The external resistor bank(Rex) allowed the arc current to be adjusted, providing a resistance between 0.15 ohms and 33.1 ohms. Three large inductors(XL), which provided the initial kick of the arc voltage across the interrupter(INT) when the magnetic contactor first closed the test circuit, were connected in series to yield an overall inductance of 12 H.

A spark gap(SG) was connected in parallel with the interrupter in order to discharge any excess overvoltage which could have stressed the test chamber. In this experiment, the gap separation was 1 mm. A cylindrical shunt(SH), which was rated at 0.0475 ohms, 100 MHz and 3% shift at 1850 Joule, was provided to measure the arc current.

3.2 Experimental Procedures and Conditions

The following test procedures were executed in each run in order to measure the arc voltage, arc current, and upstream and downstream pressures:

1) The resistance of the external resistor bank was adjusted to ensure the desired arc current value.
2) An 1.4 mil ignition wire was inserted through the hole in the electrode.
3) The electrode gap spacing and the nozzle gap spacing were adjusted to the desired value.
4) A dual beam cathode ray oscilloscope(CRO) was set to the desired value measuring the arc voltage and current. The trigger level was also adjusted so that it could be triggered externally.
5) The CRO camera shutter was set to the open position after taking a picture of the scope grid and ground level line with a Polaroid type 47 film.
6) The settings of the sequential timer were adjusted to desired values.
7) Circuit breakers CBb and CBc were closed.
8) The main valve was opened manually and slowly adjusted until the desired pressure ratio was achieved across the nozzle.
9) The limit switch of the gate was closed when the test cage gate was closed.
10) The sequential timer was activated after circuit breaker CBa was closed.
11) The CRO was triggered and the solid state relay energized by a signal from the sequential timer. The magnetic contactor was closed, establishing an arc in the test chamber. After a test duration of 300 - 500 ms (adjustable by the timer) the magnetic contactor was opened.
12) The main circuit breaker CBa, the gate limit switch, the main valve, and the two protective circuit breakers CBb and CBc, were turned off successively.
13) The CRO camera shutter was closed before pulling out the film. After analyzing the measured quantities, the data were recorded.
14) The nozzle was removed from the interrupter and cleaned in order to remove the molten ignition wire and ferric chloride. The glass side walls were taken out and replaced by new ones.

The nozzle pressure ratios revealed by the readings on the mercury manometer board can be stated in the following equation:

$$Pr = \frac{Pa}{Pa - (|h1| + |h2|)} \qquad (1.1)$$

where Pa is the ambient pressure, i.e., the stagnation pressure measured by a barometer in inches of mercury, and h1 and h2 are the displacements of the mercury surface from the reference line, representing changes in the nozzle exit pressure.

The main parameters and the experimental conditions for the low voltage dc steady arc test are summarized in Table 1.

Table 1. Summary of experimental conditions

Gas	Air
Arc Current	60 to 230 A
Electrode Gap Separation	56 mm
Nozzle Gap Spacing	12.7 mm
Nozzle Pressure Ratio	1.0 to 6.9
External Resistance	1.6 to 5.45 ohms
Test Duration	300 to 400 ms

4. Test Results and Discussion

Experimental analyses of small dc arc currents in two-dimensional, three-dimensional, and orifice nozzles have been undertaken by previous investiga-tors[6,7]. But these experiments were performed exclusively at the arc current range of 45 to 110 Amperes, and the previous results showed that the arc voltage and power characteristics of the two-dimensional nozzle were radically different with those of three-dimensional and orifice nozzles. In this research, on the other hand, the arc voltage, average electric field, arc resistance and arc power were understood to be functions of the nozzle pressure ratio in a two-dimensional nozzle with an arc current range of 60 A to 230 A. In addition, the effects of shock waves on arc characteristics were also investigated.

Fig.6 is a typical oscillogram of the test showing arc voltage and current. Figs.7 ~ 11 represent arc voltage, average electric field strength, arc resistance, arc current, and arc power as functions of nozzle pressure ratios. Each of these figures reveals a very steep slope between Pr=1.0 and Pr=1.1 and a quite smooth slope between Pr=1.1 and Pr=2.4, with almost no variation above 2.4. These characteristics are similar to those for three-dimensional and orifice nozzles, which give near constant values at pressure ratios of 1.5 and above. The values for the three-dimensional and orifice nozzles, however, are approximately 1.5 times larger than those shown in Figs.7 ~ 11. Variations at pressure ratios of 1.5 and below are so large due to the choked flow.

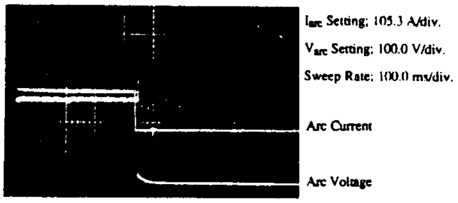

Fig.6. Typical oscillogram of the test.

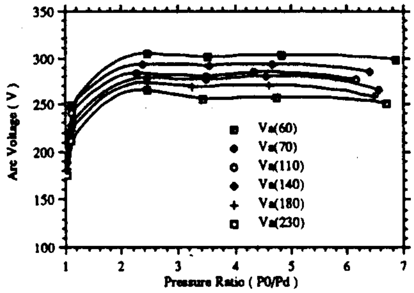

Fig.7. Arc voltage variation wrt pressure ratio at various arc current(Steady state, Air, 1 atm).

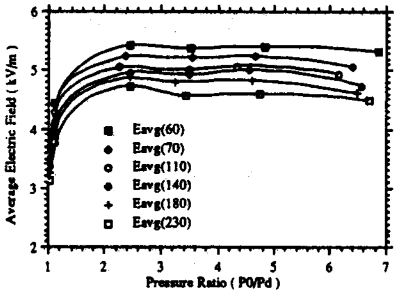

Fig.8. Average electric field variation wrt pressure ratio at various arc current(Steady,Air,1 atm).

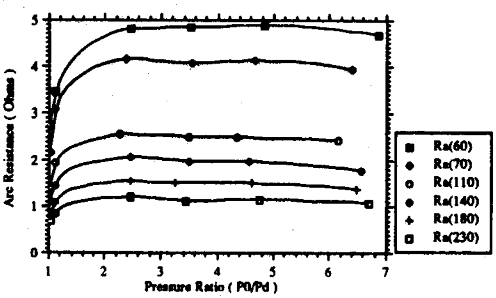

Fig.9. Arc resistance variation wrt pressure ratio at various arc current(Steady state, Air, 1 atm).

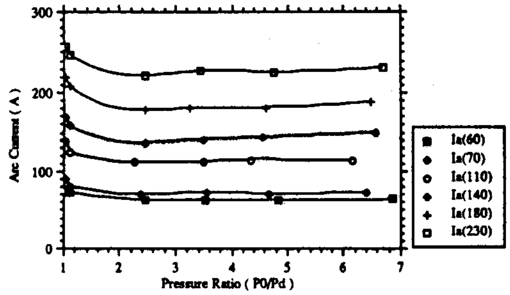

Fig.10. Arc current variation wrt pressure ratio (Steady state, Air, 1 atm).

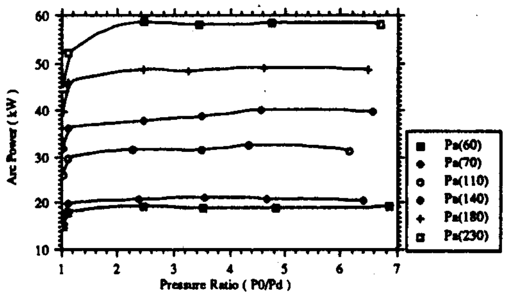

Fig.11. Arc power variation wrt pressure ratio at various arc current(Steady state, Air, 1 atm).

As the arc current increases from 60 A to 230 A, the arc voltage decreases from 300 V to 260 V, the average electric field decreases from 5.4 kV/m to 4.6 kV/m, and the arc resistance drops from 4.8 ohms to 1.1 ohms. On the other hand, the arc power increases from 19 kW to 58 kW. Tuma et. al.[8] found that thermal conduction caused an increase in the steady state arc voltage as the current was reduced within the low current region. They also found that in the intermediate current region arc voltage remained constant with arc current, while in the high current region arc voltage increased with arc current due to nozzle clogging.

Fig.12 represents the average electric field variation with respect to arc current at various nozzle pressure ratios. Shock waves were not produced in the nozzle at pressure ratios of 1.0 and 1.1 (subsonic flow). At pressure ratios of 2.46, 3.50, and 4.60, shock waves appear between the electrode and the nozzle throat. When the pressure ratio reaches 6.4, shock waves in the nozzle flow are produced downstream of the electrode. It can be inferred from this that shock waves are associated with supersonic flows, that is, at pressure ratios of 2.4 and above. Flow conditions before and after a normal shock wave can be expressed by the Rankine-Hugoniot equation[9]:

$$h_2 - h_1 = 0.5\,(P_2 - P_1)\,(v_2 - v_1) \qquad (1.2)$$

where h_1 is the specific enthalpy, P_1 the pressure and v_1 the specific volume. Shock waves can cause the arc diameter to broaden suddenly in supersonic flows, increasing the pressure, density and temperature, while decreasing the flow velocity to subsonic levels[3]. Shock waves are produced when the flow from an orifice nozzle expands rapidly and when the gas flow separates from the downstream wall of a nozzle.

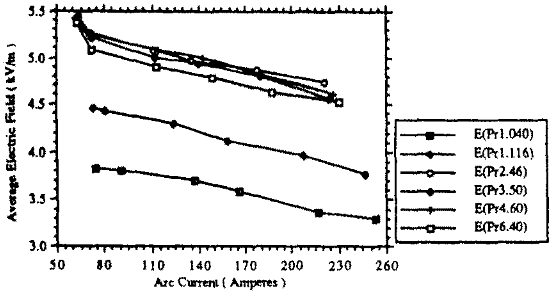

Fig.12. Average electric field variation wrt arc current at various pressure ratios.

As shown in Fig.12, the average electric field strength as a function of the arc current at nozzle pressure ratios of 1.04, 1.12, 2.46, 3.50, 4.60, and 6.40 has a negative characteristic (positive electric field strength, negative incremental value). This negative E-I characteristic, in which the average electric field strength is inversely proportional to the arc current, is typical of low current arcs[10,11,12,13]. Average electric field strength is also a function of the nozzle pressure ratio[11]. At subsonic flow speeds(nozzle pressure ratios of 1.04 and 1.12) the electric field strength decreased linearly within the current range of 60 to 260 A. At supersonic flow speeds(nozzle pressure ratios of 2.46, 3.50, 4.60, and 6.40), however, the more the arc current decreased, the stronger the elctric field strength became. The electric field strength did not vary greatly at nozzle pressure ratios of 2.46, 3.50, and 4.60 because the shock wave was produced between the electrodes in the nozzle. When the pressure ratio reached 6.40, however, the characteristic curve dropped below those for lower pressure ratios, indicating that the shock wave was produced behind the electrodes in the nozzle.

5. Conclusions

As a means of investigating the effects of shock waves on arc voltage, the average electric field, arc resistance and arc power in a model interrupter with two-dimensional dual flow nozzles, arc tests were conducted within the current range of 60 to 250 A with an upstream to downstream pressure ratio of 0.1 to 7.0. Each test measured the arc voltage, the arc current, and the upstream and downstream pressures.

The results of these tests have been analyzed to provide insights into the arc characteristics for gas circuit breakers. The following conclusions can be drawn from this research:

1) Arc characteristics such as arc voltage, average electric field, arc resistance, and arc power are a strong function of the pressure ratio determining the flow Mach number in a nozzle.

2) The characteristic curves of the two-dimensional dual flow nozzle are similar to those of orifice and three-dimensional dual flow nozzles[6,7]. All three types show a very steep slope resulting from the arc flow blocking at pressure ratios between 1.0 and 1.1, a very smooth slope at pressure ratios of 1.1 and 2.4, and almost no variation at pressure ratios of above 2.4.

3) The average electric field strength is also a strong function of the pressure ratio, and is inversely proportional to the arc current within the current range of 60 to 250 A, findings which differ from those for high currents. When shock waves are produced in front of the electrode at pressure ratios of 2.46, 3.50 and 4.60, their electric field strengths are basically the same; and they are much higher than when the shock wave is produced behind the electrode at a pressure ratio of 6.4.

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