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# A Rotating Arc Gas Pump for Circuit Breaking and Other Applications

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**Abstract**—A rotating arc circuit breaker is described which uses an auxiliary current source to generate the magnetic field for driving the arc. Test results obtained using optical fiber measurement systems have shown that there are three main arcing phases. Initially the arc rotates at an essentially constant but low velocity, subsequently its velocity oscillates between this and much higher values, and finally the arc plasma may become diffuse in nature. Test results obtained with dielectric strength probes have indicated that a unidirectional flow of arc heated gas is generated. The flow is away from the moving contact of the interrupter so promoting good dielectric strength in this critical contact region. The combination of the optical fiber and dielectric probe results indicates two possible modes of gas pumping represented, respectively, by a fan and a piston-type action of the arc. Simplified analytical models for both modes are developed with predictions obtained showing good agreement with the experimental results. Discussion of experimental results suggests that the transition from oscillatory velocity changes to diffuse arcing represents an important parameter for scaling the geometries of future interrupters and arc heaters.

**Index Terms**—Arc discharges, circuit breakers, electromagnetic coupling, helical arcs, magnetic fields effects, optical fiber measurement, SF<sub>6</sub>.

## I. INTRODUCTION

IT IS WELL known that electromagnetic forces can be used to drive electric arcs for circuit breaking and gas heating applications [1]–[6]. In general, the arc plasma column may be driven laterally between two linear and parallel electrodes, be spun radially between two annular electrodes, or be driven as a helix within an extended cylindrical electrode [1], [2].

Helical arcs are of particular interest because their implementation in circuit breakers brings many attractive benefits, such as low energy operation and freedom from the troublesome current chopping [7]. They are driven by a complex system of electromagnetic forces arising from the combination of radial, azimuthal and axial magnetic field components, produced by a coil wound around the outside of a cylindrical electrode, and similar components of the electric current flowing in the convoluted arc plasma column [1], [2].

Fig. 1 shows an example of a circuit breaker geometry which can sustain such helical arcs. In the closed position, a movable contact mates with a stationary contact. On opening

the movable contact, an arc is drawn between the movable and the stationary contacts as the former moves toward its fully open position on the axis of the annular structure. The arc is then “blown” under its own magnetic force, toward the annular structure via the contact finger. Once the arc has transferred into the annular structure, the magnetic field produced by the coil is used to both rotate the arc and move it axially so producing a helical arc column.

The control and extinction of a helical arc are highly complex physical processes, influenced strongly by both the magnetic field of the coil and the aerodynamic field of the arc-ambient gas system. This is accompanied by the arc heating the surrounding gas and so modifying the mass density and drag coefficient. There is also evidence of a bulk flow of gas axially from within the cylindrical electrode [8] although its mechanism remains to be determined. The complexity of this problem is further compounded through the magnetic field being produced by the same time dependent current as that flowing through the arc but additionally with a phase difference produced by eddy currents in the annular electrode [9]. The different time variations of current and the magnetic field produce a complicated time-dependent Lorentz force [2], while this dependence of the magnetic field upon the arc current effectively leads to the Lorentz force amplitude varying as the square of the arc current.

The purpose of this paper is to report experimental results so that the complex nature of the mechanisms producing the bulk flow of gas from the helical environment may be elucidated. In order to achieve this objective, the complex time dependence of the Lorentz force has been simplified by exciting the magnetic field producing coil independently of the arc current itself. Experimental results suggest that the movement of the helical arc during its entire extinction process may be described by three arcing phases. It is also indicated that the bulk flow of gas is unidirectional away from the movable contact and its operation has two possible modes. Simple analytical models of these two gas pumping modes are presented.

## II. EXPERIMENTAL ARRANGEMENT

A schematic of the experimental unit used for the present experiments is shown in Fig. 1 and has already been described above. The whole assembly was housed inside a steel tank. High voltage bushings were fitted to the enclosure enabling the circuit breaker electrodes to be connected to an inductively tuned capacitor bank and the  $B$  field coil to a separate critically damped capacitor bank. In addition, some connection ports

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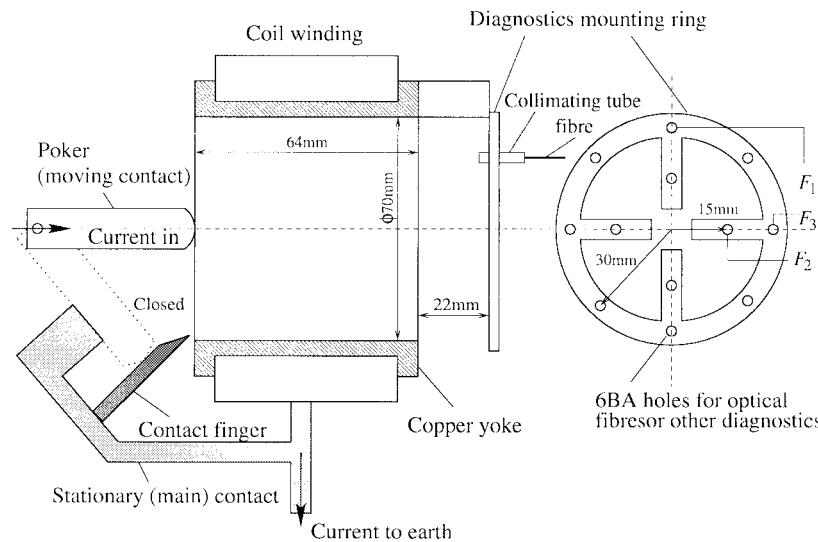


Fig. 1. Contact unit of a rotary arc circuit breaker with the diagnostics mounting ring.

were introduced to the steel tank so as to facilitate external access to the diagnostic system of the circuit breaker.

The excitation of the magnetic field producing coil could be realized in one of two ways. In a conventional rotating arc circuit breaker, one end of the coil is attached to the breaker's annular contact whereas the other is connected to the main contact. Thus the fault current flows through the field producing coil to generate an arc-driving force that is proportional to the square of the fault current. Alternatively, the coil could be excited by an auxiliary current source so as to achieve independent control of the arc movement. Fig. 2 shows the implementation of such an independently excited coil in the experimental apparatus. A current of 158 A produces a maximum axial magnetic field of 440 mT with the field distribution in space being solenoidal. As already noted, the eddy-current induces in the annular electrode a phase difference between the exciting current and the magnetic field. Full details of the field distribution and phase difference are given in [9] and [10].

Also indicated in Fig. 2 is the diagnostics arrangement for optical fibers and dielectric probes. In addition, a Dynafax high-speed camera was used to photograph the arc along the coil axis from the diagnostics ring end of the assembly. Both the high-speed camera and the optical fibers were employed to monitor the time-varying position and appearance of the fault current arc. The photographic records produced spatially detailed snapshots of the arc while the optical fiber signals gave a continuous time record at only three spatial locations. With sufficient protection, the fibers could be placed close to the arc without being susceptible to electrical and magnetic disturbances.

For the present experiment, there were three optical fibers— $F_1$ ,  $F_2$ , and  $F_3$ —placed to view the arc axially.  $F_1$  and  $F_3$  were both placed on a circumference of 30-mm radius with an angle of  $90^\circ$  apart, whereas  $F_2$  was placed on a circumference of 15-mm radius but on the same radial line as  $F_3$ . Therefore, the signals gathered by these three fibers provided the information about the arc rotation in both the

radial and circumferential directions. It has been demonstrated that three such fibers provide adequate information to draw a clear picture of the arc rotation [11]. The viewing angle of these three fibers was restricted to  $1.5^\circ$  by a collimating tube of 1-mm diameter in order to give a narrow line of sight. This provided a viewing field of only 2 mm in diameter at the arc location so that only a fraction of the arc length is observed. This results in the pulses in Fig. 3(c) being relatively sharp.

Dielectric probes of a spark gap type were introduced at both the poker and the diagnostics mounting ring end to monitor the changes in the dielectric strength of the gas in the circuit breaker [12]. These miniature dielectric probes employ a spark gap that is continually stressed so that on discharge the gap is immediately recharged until the next breakdown. Thus their operation is repetitive.

### III. EXPERIMENTAL RESULTS

A series of tests was undertaken using an independently excited coil wound uniformly on the annulus and energized by a quasi-dc excitation current. Fig. 3 shows a set of oscillograms typical of those obtained under test for an average arc current of 860 A and a gas-filling pressure of 0.3 MPa  $\text{SF}_6$ . The arc current, shown in Fig. 3(a), has an initial value of approximately 1260 A for 5 ms, then declines with superimposed oscillation until it is extinguished at 20.9 ms [not shown in Fig. 3(a)]. Particularly noteworthy is the increase in oscillation amplitude at around 17 ms. The average value of arc current between 5 and 20.9 ms is 860 A. Comparison of the arc voltage and current waveforms shows that the current oscillations between 5 and 17 ms are accompanied by a third phase in which its mean value rises again, and the large oscillation in the voltage continues. This third phase corresponds to the period of large fault current oscillation.

As the arc rotates, its light emission is received by each of the three optical fibers in turn. For the experimental conditions specified (average arc current of 860 A and 0.3 MPa  $\text{SF}_6$ ), the outputs from the fibers are in the form of a series of sharp pulses [Fig. 3(c)]. The time interval between the pulses is an

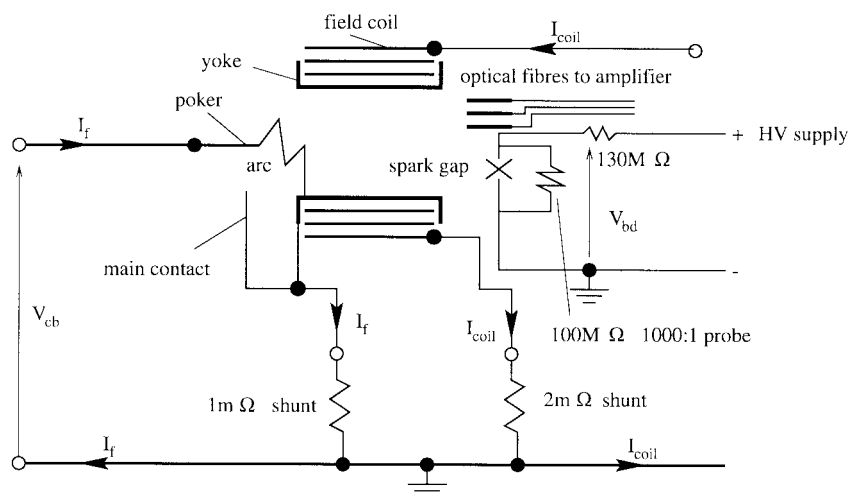


Fig. 2. Circuit arrangement for an independently excited field coil and a dielectric probe.

indication of the arc's average rotational velocity. Thus since the pulse sequence has initially a relatively long period, the arc has correspondingly a low velocity. However, at later times, the period between pulses becomes less uniform and reduces in length, implying that the arc velocity fluctuates between substantially different maximum and minimum values. Comparison with high-speed photographs shows that this phase corresponds to the onset of helical arcing. It is also of interest to note that the onset of the higher velocity phase coincides with the start of the higher arc voltage [Fig. 3(b)].

The average arc velocity over one revolution for the 860-A arc may be determined from the time difference between optical pulses in Fig. 3(c), yielding results of the form shown on Fig. 4. The velocity over one-quarter of a revolution may also be calculated using the time difference between pulses from optical fibers  $F_1$  and  $F_3$  (see Fig. 1). There are three arcing phases. Initially the arc executes a number of revolutions at a relatively low but relatively uniform velocity in the region of 5–10 rad/ms. It then accelerates into a higher velocity regime where its velocity fluctuates between this low velocity and a maximum velocity of 32 rad/ms. Finally after approximately 20 ms when the current is interrupted, the arc becomes diffuse in nature and its velocity becomes indeterminate. During the arcing period, the Lorentz force on the arc changes as both the magnetic field and arc current change. It should be noted that the high-velocity regime occurs after the peak of the magnetic field excitation current, at a time when the Lorentz force is decreasing.

The local breakdown voltage  $V_{bd}$  for the 860-A arc is measured by two dielectric probes placed at both the poker end and the remote end of the magnetic field coil as shown in Fig. 5. Both breakdown voltage curves exhibit a small dip when the fault current arc is present, and this is most likely to be due to the radiation from the arc column [12]. This small reduction in  $V_{bd}$  is then followed by a recovery. However, after arc extinction, the breakdown voltage measured at the remote end experiences a much greater reduction before it recovers back to its pre-arcing level. This reduction implies an axial displacement of dielectrically weak gas from the hot

arc region to the remote end. However, no such reduction of  $V_{bd}$  post arc is apparent at the poker end, suggesting that the gas displacement is unidirectional from the poker end to the remote end.

Measurement of the instant at the middle of the arcing period and the instant when the minimum breakdown voltage is recorded gives an approximation of the time interval for the gas to travel a distance from the poker nose to the dielectric probe, resulting in an estimate of the averaged axial speed of the gas flow  $v_g$ . Since gas density  $\rho$  can be obtained from an assumed gas temperature [13], [14], the mass flow rate may be calculated from the continuity equation of  $\dot{m} = \pi r_b^2 \rho v_g$ . Thus the combined use of the dielectric probe results (Fig. 5) and the rotational velocity results (Fig. 4) allows the gas flow effects to be related to the rotational modes of the arc discharge. The implication is that the arc rotation produces a unidirectional gas flow away from the poker and a bidirectional expansion of hot gas from the enclosed arcing volume does not appear to dominate.

Further, it may be postulated that there are two possible gas pumping modes. During the smooth, low velocity arcing phase, a unidirectional gas flow may be produced by a “fan”-like action of the rotating radial arc column. During the fluctuating, higher velocity arcing phase, it may be postulated that an additional pumping mechanism may occur, namely, a “piston”-like action produced by the repeated lengthening and short circuiting of the arc helix. Inspection of the annular contact after each and all experiments showed that wear was uniform in the area of the contact nearest the poker, i.e., the arc has no preferred path.

#### IV. GAS-PUMPING MODELS

The rotating arc under investigation is complex in nature and thus difficult to model rigorously. A simplified model is therefore suggested for gaining a preliminary insight into the arc behavior. It has been established that the rotation speed of the arc is slow immediately after it is blown into the yoke. Thus for this initial period of slow arc rotation, the arc may be considered as a linear plasma filament inclined at an angle to

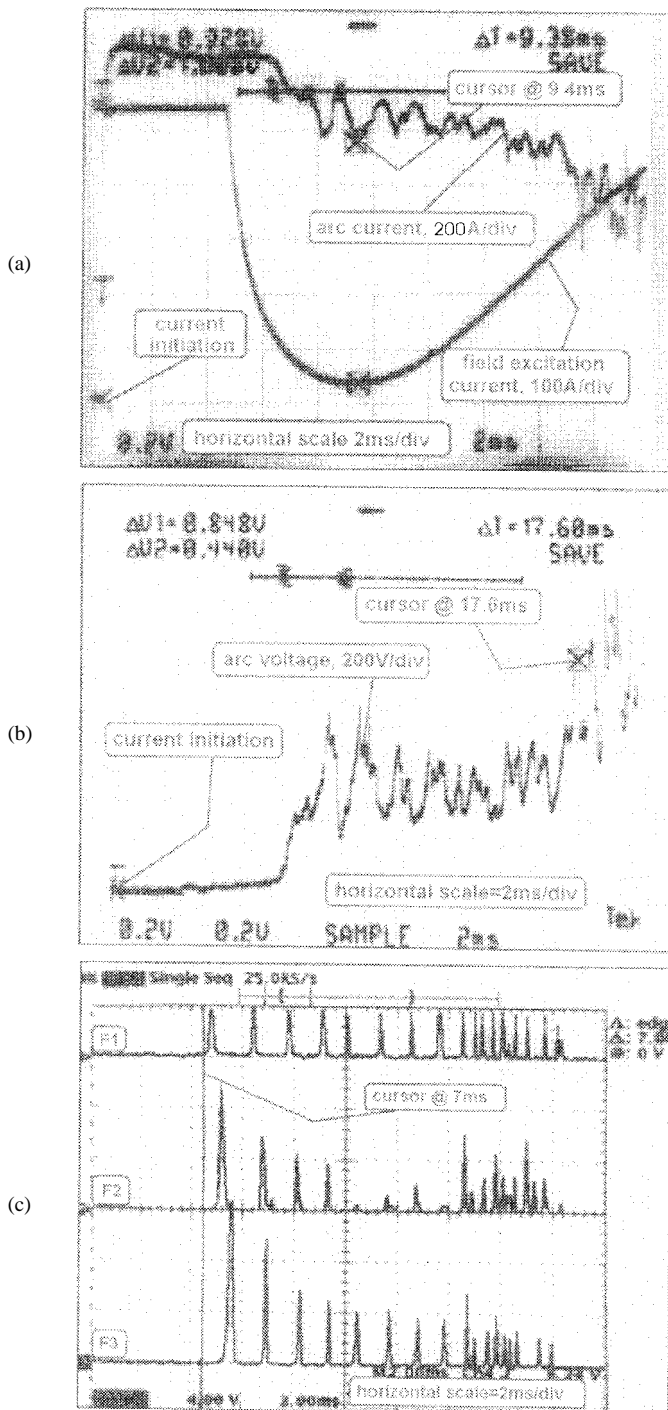


Fig. 3. Oscilloscopes of (a) arc current and coil current, (b) arc voltage, and (c) optical fiber output.

the axis of the yoke as shown in Fig. 6(a). Since the entire arc is rotating with an angular velocity  $\omega$ , the linear velocity  $v_2$  close to the annular contact is greater than the linear velocity  $v_1$  near the inner arc root, and thus the static pressure at the inner arc root is greater than that at the arc's outer root near the annular contact. This suggests that there is a pressure gradient along the length of the arc column. Note that because the column is itself inclined with respect to the yoke axis, the pressure gradient will have an axial component. Consequently,

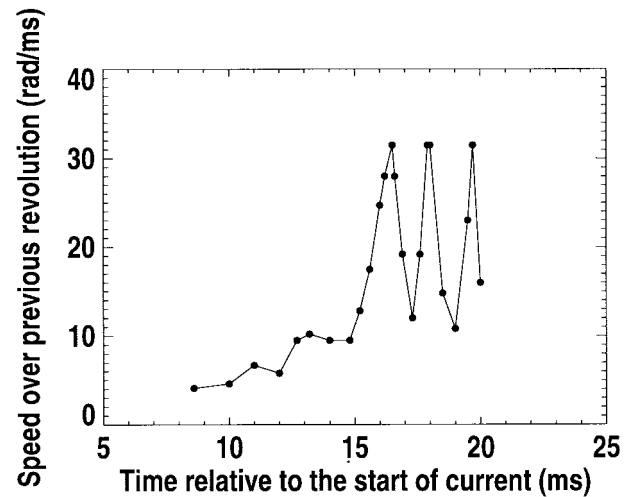


Fig. 4. Velocity evolution of arc in a uniformly wound field coil.

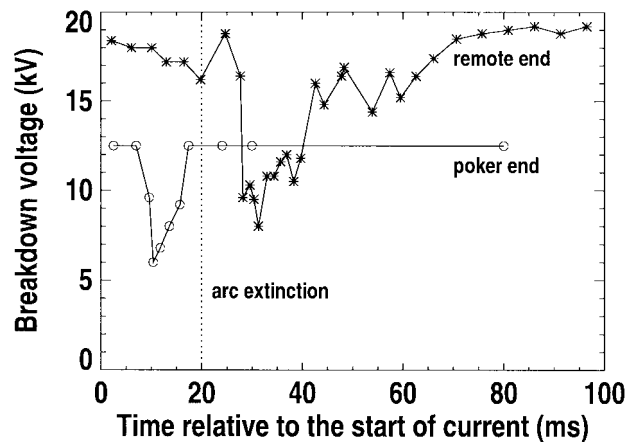


Fig. 5. Dielectric probe responses after current initiation.

the arc may act like a single-bladed fan, in which the blowing action would increase as the arc extends toward the remote end and its angle  $\phi$  decreases. Data from the two radially lined optical fibers  $F_2$  and  $F_3$  in Fig. 3(c) support such a fan model since the light emission of the arc arrives at  $F_2$  and  $F_3$  at approximately the same time in the first 10 ms of arcing.

As the arc rotates more rapidly, the difference between the peripheral and central velocities [ $v_1$  and  $v_2$  in Fig. 6(a)] increases such that the aerodynamic drag force on the arc's outer root becomes significantly greater than that on the arc's inner root. Thus the arc's outer root on the annulus gradually falls behind its inner root on the poker as illustrated in Fig. 6(b). This leads to the arc having a significant circumferential component of current which reacts with the radial and axial components of magnetic field to produce axial and radial forces, respectively. The combined effect of all three force components is to produce a three-dimensional expanding helical form to the arc, which drives hot gas in a downstream axial direction. The radial expansion of the arc eventually causes part of the column to be short circuited, by contact with the outer electrode, and evidence shows that the arc then reforms near the "poker" end of the system in cold gas at a low velocity. Subsequently it rapidly accelerates giving rise to

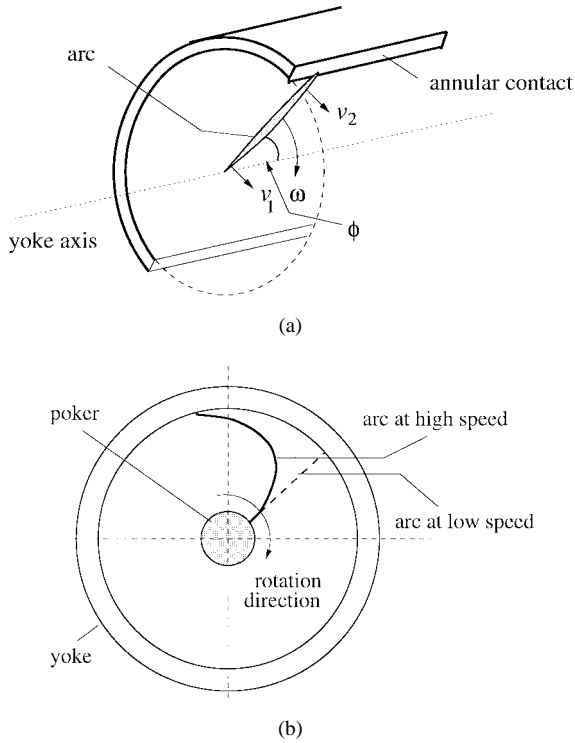


Fig. 6. (a) An idealized arc inclined at an angle to the yoke axis. (b) Arc shape at high rotation velocity.

the oscillatory section of the waveform shown in Fig. 4. This mode of fast arc rotation may be considered as a piston which repeats the process of first moving axially toward the remote end, making contact with the annulus and then short-circuiting back toward the poker.

With the above two arc models, the induced gas flow in the axial direction may be formulated to compare with the experimental results. For the fan arc model, an element of the arc experiences a lift force [13]

$$dF_L = 4\pi b\rho\omega^2 a^2 \quad (1)$$

where  $a$  and  $b$  are the radii of the arc column and of the rotation of the arc element about the axis, respectively,  $\rho$  is the gas ambient density, and  $\omega$  is the rotational velocity of the arc. This lift force leads to a steady state force  $F_r$  moving the fluid at a velocity  $v$  in a direction normal to the axis of the inclined arc

$$dF_r = v^2 \rho dA_a \quad (2)$$

where  $dA_a$  is an elemental plane area of the arc. Consequently, the axial mass flow rate of gas produced by the fan action can be formulated by integrating along the arc from the axis to the annular contact yielding [13]

$$\dot{m} = \pi r_b^2 \rho \sin \phi \sqrt{\pi \omega^2 a z \sin \phi} \quad (3)$$

where  $z$  is the extent of axial displacement of arc root on the annular contact, and  $r_b$  the radius of the annular contact.

For the piston arc model, on the other hand, a simplified form of the momentum conservation equation may be written

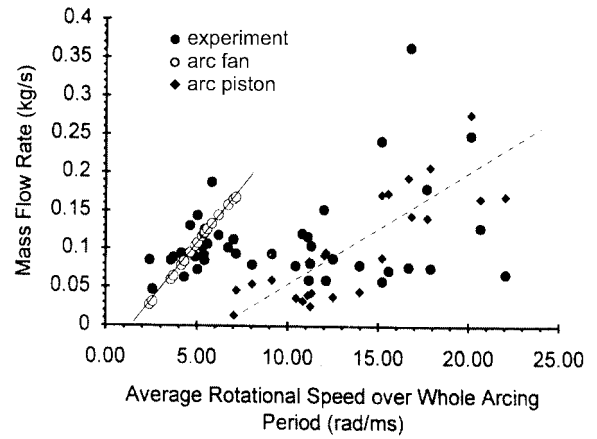


Fig. 7. Comparison of experimental mass flow rate with that calculated with the two arc models.

as the balance between the magnetic force on the arc and the axial momentum transferred to the surrounding gas

$$B_r i_c s = \frac{1}{2} \rho v^2 s d C_d \quad (4)$$

where  $B_r$  is the radial magnetic field,  $i_c$  is the circumferential component of arc current,  $s$  is the circumferential length of the arc,  $d$  is the arc diameter, and  $C_d$  is the drag factor. This leads to the formulation of the axial mass flow rate due to the piston action as follows [13]:

$$\dot{m} = 2\rho s a \sqrt{B_r i_c / a \rho C_d}. \quad (5)$$

To verify the two proposed models, the mass flow rate of the gas is measured and compared with both the fan and the piston models. Fig. 7 shows that mass flow rates of the order of 0.2 kg/s are produced by each mechanism with the ‘‘fan action’’ dominating for relatively low arc rotation velocity ( $0 < \omega < 8$  rad/ms) and the ‘‘piston action’’ dominating for typically  $7 < \omega < 25$  rad/ms for the conditions of Fig. 3. Therefore, the actual gas pumping process may be reliably described by the arc fan and the arc piston models.

It is seen from Fig. 7 that the mass flow rate for the arc fan operation at low rotational velocities is higher than that for the piston operation. Also noteworthy is that the scatter of the results in the piston mode is higher than that in the fan mode because the arc in the former mode is less stable.

## V. CONCLUSIONS

Experiments performed with an independently excited magnetic field coil in a helical arc device have shown that there are essentially three phases in the arcing period, characterized by distinctively different arc velocities. Unidirectional bulk flow of the gas has been confirmed, for which there are two possible operational modes. Simple analytical models for both gas pumping modes have been developed with predictions in good agreement with the experimental results.

The combined experimental and theoretical results of Fig. 7 show that the fan mode of operation has a higher rate of axial gas flow for low arc velocities (up to approximately 15

rad/ms), but at higher velocities the piston mode can move gas at a higher rate. Clearly it is important in device design to understand the effects of changing the size and shape of the arc device. Consideration of the two equations developed for the mass flow rate shows that the latter is much more sensitive to circuit breaker size in the fan mode than it is in the piston mode. The equations suggest that an increase in diameter of the annular electrode from 60 to 120 mm will increase the "fan" driven mass flow rate fivefold while only producing a 50% increase in the "piston" driven flow rate.

Within a given size constraint on a circuit breaker, one aspect of the shape that can be changed is the form of the magnetic field. If the distance that the arc penetrates into the coil were restricted, it is possible that the boundary between fan and piston modes may be changed and that the repetition rate of the "piston" may be increased. Preliminary experimental results have indicated that by shifting the point of zero radial magnetic field from the center of the coil toward the poker end by 25% of the half length of the yoke delays the onset of the oscillatory velocity variation (Fig. 4) to 19 ms compared with the 15 ms of that figure. Furthermore, the magnetic field produced by an independently excited coil may be controlled to have both a spatial and temporal dependence to achieve an even greater degree of arc control and hence a more efficient transfer of the arc energy to the ambient gas. This will be addressed in a forthcoming note.

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*Engineering Handbook*.

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