High current arc erosion on copper electrodes in air

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Abstract—**An arc fault inside metal enclosed switchgear will cause the pressure to rise and vaporization of electrode material may contribute to the pressure rise. An experimental study of high current arc erosion on copper electrodes in air has been performed, with an evaluation of fraction lost by gross melting and vaporization. All experiments were performed at NEFI High Voltage Laboratory in Skien, Norway. The measured mass loss from vaporization in our experiments seems to be negligible compared to erosion by gross melting.**

Keywords-component; moving arc, copper, melting, vaporization

I. INTRODUCTION

An arc fault inside a metal enclosed switchgear will cause a rise in pressure and may thereby endanger the operating safety of personnel. The rise in pressure, mainly caused by the arc energy input to the insulating medium, is a function of several variables such as electrode material, short circuit current, insulating medium, arc duration, and electrode separation.

Vaporization of electrode material may increase the gas density and thus contribute to the pressure rise. The metal vapors may in addition react with the insulating gas in chemical reactions, which again may contribute to the energy input and the rise in pressure of the gas. In the following, it is assumed that the possibility of having a chemical reaction between a metal and an insulating medium is much higher when metal is lost by vaporization than by gross melting. In the latter case, the metal is mainly eroded and lost by macroscopic droplets.

Through the years much has been reported regarding the erosion of electrode material. See, for example references [1-3]. This is typically achieved by weighing the electrodes before and after arc testing, without taking into account the mechanism of mass loss (gross melting or vaporization). Wilson [2] observed that a substantial part of the total erosion is by gross melting and by droplets ejected from the electrodes. However, a more systematic evaluation of the fraction of the mass loss that is caused by vaporization in relation to the mass loss by gross melting, is still of interest, especially in the context of arc faults in enclosed switchgears.

This paper presents an experimental method to compare, within orders of magnitude, the erosion by gross melting and erosion by direct vaporization of copper (Cu) electrodes in air. This is achieved by constructing an arrangement of Cu plates around the arc to collect most of the liquid drops. Both stationary and a moving arcs were investigated, with similar conditions regarding current and arc duration.

Based on the experimental results, the energy required for melting and vaporization, and a positive contribution from chemical reactions with the surrounding gas is estimated.

II. THEORY

The total erosion rate, E_r, of the electrodes caused by the arc, is determined from

$$E_r = \Delta m_e / Q = (1.11 \cdot \Delta m_e)/(I_{rms} \cdot \Delta t), \tag{1}$$

where Δm_e is the total mass loss, Q the electric charge, I_{rms} the arc current and Δt is the arcing time. It is assumed that the total mass loss of the electrodes, Δm_e, can be divided into two parts

$$\Delta m_e = \Delta m_m + \Delta m_v, \tag{2}$$

where Δm_m is the fraction of electrode material lost by gross melting and Δm_v is the mass lost by vaporization. The energy, W_{mv}, required for the melting and vaporization of electrode material is given as

$$W_{mv} = c_p^S \cdot \Delta m_e (T_m - T_a) + w_m \cdot \Delta m_e + c_p^L \cdot \Delta m_v (T_b - T_m) + w_v \cdot \Delta m_v, \tag{3}$$

where c_p^S and c_p^L are the specific heat capacity at constant pressure for the solid and liquid phase. w_m and w_v are the specific melting heat and vaporization heat of the electrode material. T_m, T_a, and T_b are the melting, ambient, and boiling temperature, respectively.

The fraction of the total arc energy which is required to obtain the measured electrode mass loss, from both gross melting and vaporization, is given as k_{mv} and is defined as

$$k_{mv} = W_{mv}/W_{arc}, \tag{4}$$

where W_{arc} is the total arc energy given by arc voltage, current and duration. For a precise determination of the k_{mv} -factor, the fraction of mass eroded by gross melting only and the fraction of mass eroded by vaporization need to be known.

The metal vapor may react chemically with the insulating medium, in our case air, resulting in an energy release W_{chem} (exothermic reaction). The possible chemical reactions of copper vapor and air (oxygen) are

$$Cu + 1/2O_2 \rightarrow CuO + 155 \text{ kJ/mol} \tag{5}$$

$$2Cu + 1/2O_2 \rightarrow Cu_2O + 167 \text{ kJ/mol.} \tag{6}$$

In the experiments with the moving arc, the arc motion is caused by the Lorentz force given as

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \quad (7)$$

where F is the volumetric magnetic force density, J is the current density of the arc and B is the magnetic flux density. The magnetic forces are at a minimum when the arc is parallel to the field and at a maximum if it is perpendicular to it.

In our case, the motion of the arc is caused by the test current in a special electrode arrangement, see Fig. 1. The magnetic force driving the arc will be highest at the arc roots where the magnetic field is highest. The arc motion can be influenced by changing the length of the inclined conductors, f, the angle of the conductors, or the gap distance between the electrodes, L.

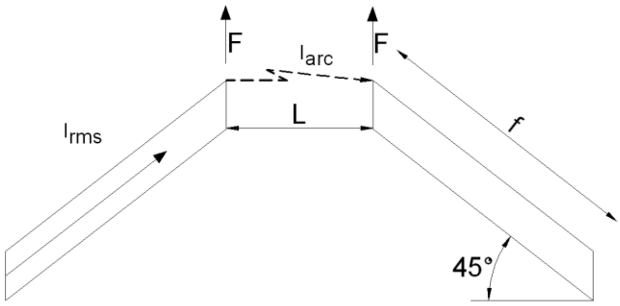

Figure 1. The test current, I_{rms}, will cause magnetic forces, F, on the arc because of the test current angle with the arc path (45º). The "finger" length, f, (length of the inclined conductors) and the gap distance between the electrodes, L, are indicated.

III. TEST OBJECTS AND EXPERIMENTAL SETUPS

The experiments were carried out with Cu electrodes in a single phase AC arrangement in open air with an arc duration of 1 second. The electrodes were connected to a source of current, and to ground potential. The arc was initiated with a thin exploding wire. The test object itself was fixed on a nonmagnetic metal rack with insulators. The gap distance L used in the experiments varied from 20 to 100 mm. The test current was 5, 10, and 16 kA_{rms} with a circuit voltage of 12, 4.76 and 4.76 kV respectively. The magnitude of the circuit voltage combined with a low power factor (less than 0.17) secure reignition at each current zero.

When an arc is initiated there are typically two conditions; stationary and moving arc. To simulate the stationary arc situation, cylindrical electrode rods of 20 mm diameter were used as electrodes. For this setup, a measurement technique was applied where the metal eroded from the electrodes by gross melting could be collected. In order to achieve this, a cylindrical shield was used to catch the molten drops. This was chosen because a fully closed container would give a pressure rise that would interfere with the arc. In order to be able to collect eroded material ejected longitudinally, disc-shaped end shields were applied in a separate test. This is shown in Fig. 2 and 3. By doing these tests, it is assumed that the total electrode mass lost by means of gross melting, Δm_m, is the sum of the mass collected on the cylindrical shield, Δm_c, and on the end shields, Δm_d, i.e.

$$\Delta m_m = \Delta m_c + \Delta m_d. \quad (8)$$

According to equation (2) and (8), the total electrode mass loss can be divided into the following parts

$$\Delta m_e = (\Delta m_d + \Delta m_c) + \Delta m_{rest} \quad (9)$$

where Δm_{rest} is the residual mass loss that is not collected by the Cu shields. According to [2] this value may represent an estimate of the mass lost by vaporization, Δm_v.

By having a constantly moving arc, it is expected that the gross melting of the electrodes would be substantially reduced. Without gross melting it is assumed that the erosion is mainly caused by vaporization. Measurement of the electrode mass loss in this mode may give a better indication of the fraction that is vaporized.

To achieve a moving arc, two contrate cup-shaped electrodes shown in Fig. 4 were made. The cup-shaped electrodes are designed based on well known principles from commercial vacuum interrupters. Radial magnetic fields, caused by current passage through the specially designed electrode structures, will make the arc rotate.

A more detailed description of the different experimental setups is given in the following subsections. All experiments were performed at NEFI High Voltage Laboratory in Skien, Norway. In all the experiments arc voltage and current were measured and recorded by the metering system at the laboratory. The electrodes were weighed before and after each test to determine Δm_e. The accuracy of the weighing process was limited to approximately ± 1 g. A high-speed camera was used to study the arc behavior, such as possible melted metal drops ejected from the electrodes and the rotation frequency of the moving arc.

A. *Stationary arc. Measurement of radial ejection - Δm_c*

This experimental setup was carried out with an open ended cylinder with an inner diameter of 400 mm and a length of 400 mm as shown in Fig. 2. The relatively thin Cu-collector was placed inside a supporting cylinder of aluminum (Al) in order to reduce the weight of the collector itself. The collector was weighed before and after testing, and it was replaced with a new one before each test.

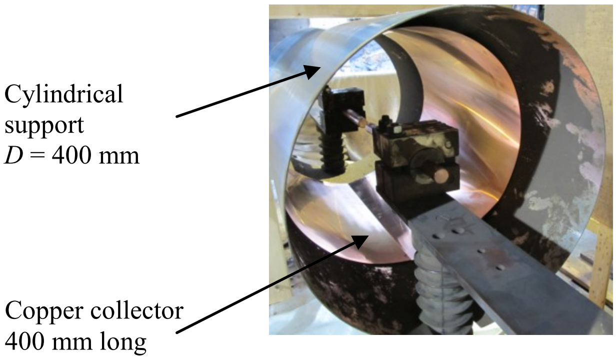

Figure 2. Stationary arc and measurement of Δm_c. The electrodes were cylindrical rods of 20 mm diameter. Cylindrical Al support with inner diameter, *D,* of 400 mm with a Cu shield inside to collect any molten drops ejected radially. Photo from test setup at NEFI.

B. Stationary arc. Measurement of longitudinal ejection - Δm_d

Two Cu disc shaped collectors were mounted vertically, see Fig. 3. The discs were 400 mm in diameter and the distance between them was 400 mm. The relatively thin Cu collector was held up by an Al support. The Cu collector was weighed before and after testing, and it was replaced with a new one before each test.

Electrode distances and current regions are in order of magnitude within typically compact switchgears for medium voltage systems. Three different specific values for test current were chosen. The gap distances were chosen to give total arc energy equivalent to the energy release with a moving arc. Table I gives an overview of the experimental conditions applied to the stationary arc.

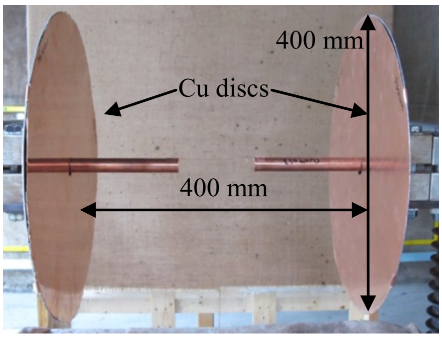

Figure 3. Stationary arc and measurement of Δm_d The electrodes were cylindrical rods of 20 mm diameter. Cu disc collectors were mounted vertically (upheld by Al support) to collect molten drops ejected in the longitudal direction. Photo from test set up at NEFI.

TABLE I. EXPERIMENTAL CONDITIONS WITH STATIONARY ARC

Test no	Experimental conditions		
	I [kA]	***Collector type***	***L [mm]***
1	5	Discs	45
2	5	Cylinder	45
3	10	Discs	30
4	10	Cylinder *	30
5	16	Discs	20
6	16	Cylinder *	20

* Was destroyed during experiments

C. Investigation of erosion with moving arc

The test objects were two contrate cup-shaped electrodes that were mounted parallel as shown in Fig. 4. The special shape of the electrodes was applied in order to obtain a radial magnetic field component to the arc, with the aim of making the arc rotate on the electrode surface.

Each test object had 12 chamfered fingers with angles of 45°. The gap between the fingers was 3 mm. The outer and inner diameters of the contacts were 100 mm and 80 mm respectively. The slits of the contact pair were contrate to each other, so that one finger pair can be considered to correspond to the situation in Fig 1. The electrode surfaces were machined to original shape (surface) after each test, resulting in a reduction in the finger length *f* between each test. Table II gives an overview of the experimental conditions applied with the moving arc.

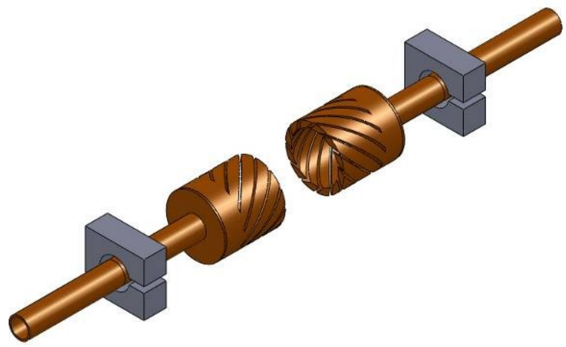

Figure 4. Contrate cup-shaped Cu electrodes used to produce a moving arc.

TABLE II. EXPERIMENTAL CONDITIONS WITH MOVING ARC

Test no	Experimental conditions		
	I [kA]	***f [mm]***	***L [mm]***
7	5	85	100
8	5	79	50
9	5	70	50
10	10	58	50

IV. EXPERIMENTAL RESULTS

Measurements of the total mass loss for stationary arc, together with (1), give an erosion rate of about 19 g/kC, independent of the arc current. This is within reasonable agreement with measurements reported by Wilson [2].

From the experiments where molten metal drops were collected (stationary arc test 1 and 2) the following relationship may be derived;

$$\Delta m_c = 5.6\ \Delta m_d. \tag{10}$$

The Cu collector inside the supporting cylinder was destroyed during test 4 and 6 due to melting caused by the extreme energy input from the molten particles hitting the surface. For these two tests an estimate for the amount of collected material, based on measurements from test 1, 2, 3 and 5 was made. It was assumed that the relationship given in equation (10) is independent of the test current and electrode gap distance for the given experimental arrangement. The measurement of Δm_d in test 3 and 5, together with equation (10), gives an estimate of the expected Δm_c in test 4 and 6. Based on this and on measurements of the total electrode mass loss, the residual mass loss Δm_{rest} was calculated. The results are shown in Fig. 5. From the figure, it can be seen that with an electrode gap of 45 mm and test current of 5 kA (test 1 and 2), approximately 70 % of the total electrode erosion was collected on the Cu discs and cylinder.

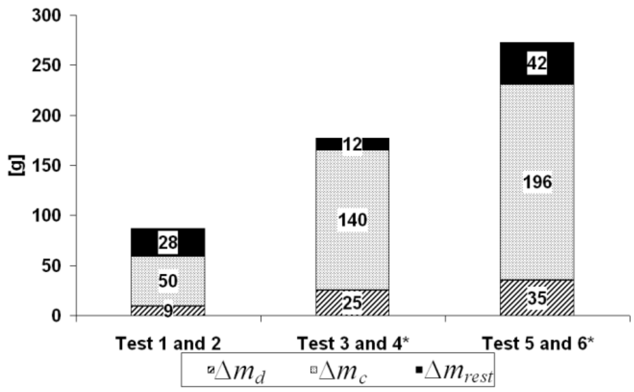

Figure 5. Total mass loss from the electrodes Δm_e reconstructed as the mass collected on the discs Δm_d and cylinder Δm_c and a residual mass loss Δm_{rest} for test 1 to 6. Test 4* and test 6* were destroyed during the experiments and Δm_c and Δm_{rest} are estimated values for these tests.

Based on measurements of the total electrode mass loss, a lower limit of the k_{mv} -factor can be calculated from (3) and (4) by assuming that all mass is lost by gross melting only. Similarly, an upper limit can be calculated by assuming that all mass is lost by vaporization. However, a more correct k_{mv}-factor can be calculated by using the results given in Fig. 5 and the same assumption as Wilson [2] i.e. that the residual mass loss is vaporized. All these values are listed in Table III. From the table, it is clear that the real value of the k_{mv}-factor is much closer to the lower limit than to the upper. E.g. the results show that 11 % of the arc energy in test 3 and 4* are required to transform the electrode mass loss to melted material, while 76 % of the total arc energy is required if it is assumed that the erosion is by vaporization only. By using Wilson's assumption, 15 % of the arc energy is required to account for the electrode mass loss.

TABLE III. CALCULATED K_{MV} -FACTOR FOR THREE DIFFERENT ASSUMPTIONS REGARDING THE ELECTRODE MASS LOSS

Assumptions	**Experimental conditions**		
	Test 1 and 2	***Test 3 and 4****	***Test 5 and 6****
All melted	0.13	0.11	0.09
Residual mass loss (Δm_{rest}) is vaporized	0.38	0.15	0.17
All vaporized	0.90	0.76	0.63

Results from the experiments with a moving arc are shown in Table IV. No gross melting is observed with the moving arc in test 7 to 9. The electrode erosion at 5 kA_{rms}, restricted now to vaporization as the dominant factor, is not measurable with our equipment. This implies that the erosion is in the order of 1 gram or less.

TABLE IV. EXPERIMENTAL RESULTS WITH MOVING ARC

Test no	**Experimental conditions**		
	I [kA]	***v*** [m/s]	Δm_e [g]
7	5	47	<1
8	5	74	<1
9	5	71	<1
10	10	109	50

In Table IV, the average rotation speed v of the arc is also listed. The rotation frequency and moving velocity of the arc was estimated by studying the high speed videos and counting the number of rotations per second. The rotational frequency for test 8, 9, and 10 was determined from 11 samplings during the arc duration of 1 sec. Observations in test 7, with a gap distance of 100 mm, show an erratic arc behavior and the arc velocity was difficult to assess. Therefore, results from test 7 are only based on the two samplings (where an intermittent semi-stable arc rotation was observed) that it was possible to make during the arc duration of 1 sec.

From Table IV it can be seen that the average arc velocity v increases as the test current increases from 5 to 10 $kA_{rms.}$ In test 8 and 9 the length of the electrode fingers is the only parameter that has been changed. Reducing the finger length gives a reduction of the arc velocity. Increasing the electrode separation (test 7) leads to a lower arc velocity.

V. DISCUSSION

Experiments were carried out to collect metal droplets ejected from Cu electrodes in open air. Trying to collect all the mass which is ejected as molten drops is a challenging task. A fully closed container would give a pressure rise that would interfere with the arc. However, by doing the measurements in two different steps (cylinder and discs), the arrangements will affect the exhaust from the arc to a certain degree. This may lead to a systematic error causing an underestimate of Δm_m. Some vaporization of molten droplets may take place, but it is assumed to be of minor importance. In addition, assuming that equation (10) is independent of the test current and electrode gap, is a rough estimate. Thus, the results can only be used to get an estimate of the order of magnitude of the fraction of arc erosion caused by gross melting.

After each experimental test, a visual inspection of the Cu collectors was made. Droplets that had splashed and melted on the Cu shields could be observed as shown in Fig.6. Metal vapor collected on the collector surface may have been present, but it was concluded that the possible contribution to the total mass gain was negligible.

The distribution of droplets on the Cu plate was also studied. The drops collected on the Cu discs in Fig. 3, seemed to be symmetrically distributed around the center. Melted drops collected on the Cu plate placed inside the cylinder in Fig. 2, clearly show two areas with high density of collected drops. This is shown in Fig. 7. These areas correspond to the areas directly beneath and above the arc, and could be caused by gravitational forces and heat convection, respectively.

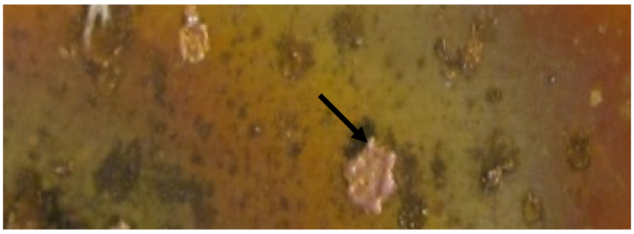

Figure 6. Droplets melted on the Cu collectors observed after test 1.

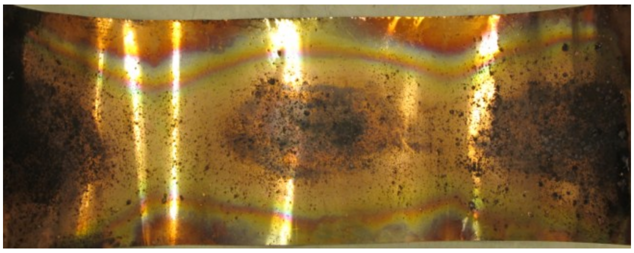

Figure 7. Dissipation of droplets on the outstretched copper plate after test 2 showing clearly two areas (top and bottom) with higher density of molten droplets.

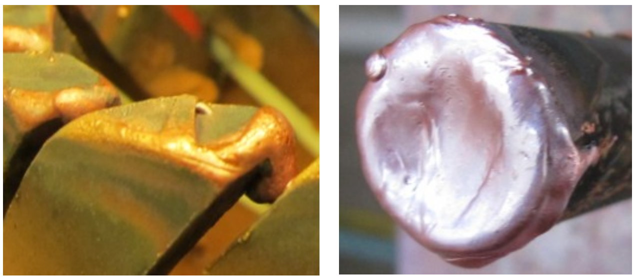

Figure 8. Left: Shape of the electrode fingers with a moving arc after test 8. Right: Shape of cylindrical rod after a test with a stationary arc .

Based on the simplified assumptions regarding how the arc behavior and distribution of ejected vapor and droplets could possibly be influenced by a set of collectors, approximately 70% of the total erosion loss was collected with a test current of 5 kA. In Wilson's experiments [2] approximately 45% of the erosion was collected on an insulating cup placed around the arcing contact at 12 kA. A direct comparison of the results is not possible due to differences in the experiment setup. If we apply Wilson assumption on our experimental results (from 3 and 4* with 10 kA), 15 % of the arc energy is required to get the measured electrode mass loss.

The moving arc velocity at currents between 5 and 10 kA was found to be in the order of 50 to 100 m/s. Earlier reported arc traveling velocities are found within the same range [4]. The arc velocity is observed to increase with increasing current because of the increased magnetic force, according to equation (7). The observed reduction in velocity when the finger length is reduced is explained by a reduction in the magnetic field. The random behavior of the arc in test 7 may be caused by the larger gap distance, whereby the interaction between the arc and the self generated magnetic field could become unstable.

As the arc rotates, it will cause a repetitive heat input to the electrode surfaces, and surface melting is observed. Figure 8 shows the shape of one electrode finger after moving the arc in test 8 and the shape of one cylindrical electrode after a test with stationary arc. It can be seen that the fingers shape and surface changed during the experiments and some droplets were observed inside the electrode cup. This could be the result of repetitive energy input from the rotating arc. From high speed video of test 10 (performed with 10 kA_{rms}), it is clear that the arc velocity is reduced towards the final part of the arcing time. At this time, the surface melting as seen in the left part of Fig. 8, has filled most of the gap between the fingers. This will disturb the arc motion. When the rotation velocity is substantially reduced, we can no longer assume no gross melting. The 50 grams of mass loss measured on the electrodes in this case given in Table IV, is believed to be caused by gross melting towards the end of the arcing time.

With dimensions of metal enclosed switchgear at medium voltage normally in the range of about 1 m per cubicle, a possible fault arc will be stationary for most part in a standard one second arc fault test. Consequently most of the erosion observed will therefore be by gross melting and droplets.

As mentioned earlier the metal vapor may react chemically with the insulating medium, in our case air (or rather oxygen), resulting in an additional energy release W_{chem}. This may then contribute to an increased rise in pressure if the arc occurred inside a closed container. To get a better understanding of the influence of chemical reactions, it is assumed that the reactions contribute significantly only if the released energy is more than 10 % of the total arc energy. Table V shows the assumed amount of copper, Δm_{Wchem}, which will have to react chemically, according to equation (5), for a 10 % extra contribution to the arc energy input. It may be assumed that an exothermic reaction will to a large extent depend on Cu being present in vapor form. The calculated values are thus compared with the electrode erosion mass that was not collected at the Cu-collectors during our experiments. As can be seen from Table V, the required mass loss is higher than the residual mass loss from the experiments in all tests. At a first approximation it may be concluded that the extra energy input caused by Cu vapors reacting exothermally with the surrounding air is most probably negligible. This is however in contrast to the strong exothermal reaction between vaporized aluminum and dissociated SF_6 reported by Bjørtuft et al. [5].

TABLE V. CHEMICAL REACTION BETWEEN CU AND AIR

Test no	**Results**		
	W_{arc} [MJ]	Δm_{Wchem} (10 %) [g]	Δm_{rest} [g]
1 and 2	0.699	29	28
3 and 4*	1.690	69	12
5 and 6*	3.140	129	42

For the moving arc with no gross melting, relevant information is relatively scarce in the literature. It has earlier been concluded by Wilson [2] that the electric arc in air (or any medium) to a large extent burns in metal evaporated from the electrodes. Very soon after arc initiation the original medium is replaced by ionized metal vapor as the conducting medium. Based on this assumption it could be relevant to compare our moving arc results with the cathodic erosion rate of copper in a vacuum arc (metal vapor). An erosion rate of 80 µg/C at a test current of 5 kA (so-called A–mode, without gross melting) is reported by Rondeel [6]. When related to our experiments, this erosion rate should result in an expected mass loss of 0.4 g Cu at 5 kA. With the limited accuracy of our measurements, as earlier mentioned, we only know for certain that the erosion is less than 1 gram. Results from the moving arc indicate that the measured mass loss from vaporization in our experiments seems to be insignificant compared to erosion by gross melting. Arc energy required to get the measured electrode mass loss is probably close to 10 %.

The cylindrical collector in test 4 and 6 was destroyed during tests. To get experimental results from these tests the diameter of the support and collectors should be increased.

Conclusions were based on single test runs. More repeatable results should be produced in the future to verify the estimates presented in this paper.

Especially further experiments should be done to examine and compare the amount of vaporized mass loss from stationary and moving arcs.

VI. CONCLUSION

The electrode erosion rate for the stationary arc was measured to be 19 g/kC, independent of the arc current. Approximately 70 % of the total erosion loss was collected as droplets with a test current of 5 kA_{rms}. Most droplets were caught directly above and beneath the arc. By assuming that the residual mass loss is vaporized, approximately 15 % of the arc energy is required to obtain the measured mass loss at 10 kA_{rms}. The results from the moving arc indicate that the value is probably close to 10 %. This means that the measured mass loss from vaporization in our experiments seems to be insignificant compared to erosion by gross melting. Thus, only a small fraction of the eroded copper can react chemically and the influence on the pressure rise from chemical reactions is negligible during an arc fault inside a medium voltage switchgear enclosure. Based on these results it could be concluded that the main contribution to the pressure rise in equipment with air insulation and copper electrodes is through direct heating (radiation and convection) from the arc.

ACKNOWLEDGMENT

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