CLOUD FORMATION DURING HIGH CURRENT ARCS IN AIR

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ABSTRACT

The aim of this paper is to study the cloud of gas and particles formed around high current arcs. A high-speed camera will be used to study the arc cloud formation. In addition measurements of the radiation escaping from the cloud will be performed. Electrode material, gap, test current, and movement of the arc were found to influence the properties of the arc cloud. Preliminary results with frame subtraction method indicate that this is a method which is useful when studying the arc cloud formation.

1. INTRODUCTION

Arcs dissipate large amounts of energy into its surroundings by conduction, radiation, and convection. Some of this energy is transferred to the electrodes. If the power delivered to the electrode surfaces exceeds the amount which can be conducted through the electrodes, the temperature of the electrodes may reach the boiling point. Then metal vapour together with metal droplets may enter the surrounding gas.

The melting and vaporization of the electrode material and the following combustion processes cause a cloud of gas and particles to develop around the arc. This “arc cloud” is believed to influence the energy transfer processes. The properties of the cloud depend on the electrode material [1], the amount of eroded metal [2], and the chemical energy release during chemical reactions.

The aim of this paper is to study the cloud of gas and particles formed around high current arcs. A high-speed camera will be used to study the arc cloud formation. In addition measurements of the radiation escaping from the cloud will be performed to provide additional information. The measurements were performed for an arc burning in open air in a single-phase arrangement.

2. EXPERIMENTAL

Fig. 1 shows the simple single-phase arrangement built for the tests. The basis was two horizontally opposed electrodes with a gap, *g*, which could be varied from 17 to 200 mm. A thin Cu-wire with a diameter of 0.5 mm was used to ignite the arc between the electrodes. The arc duration was 1 second, which is typical for internal arc fault testing of medium voltage switchgears in Europe.

All experiments were performed at NEFI High Power Laboratory in Norway. The power source supplied an alternating test current with a frequency of 50 Hz. The short circuit current varied from 5.1 to 16 kA.

When an arc fault occurs inside a switchgear, the magnetic field will make the arc run along the busbars away from the source. However, for most of the arcing time, the arc will burn at a more or less fixed place [3]. To simulate both a stationary and a moving arc, two different electrode shapes (shown in Fig. 2) were used in the experiments: Cylindrical rods with 20 mm diameter were used to simulate the stationary arc as the arc root motion will in this case be in within a highly restricted area. Electrode materials were Cu and Al. The moving arc was simulated using two cup-shaped Cu-electrodes designed by Oyvang et al. [3] on principles from commercial vacuum interrupters.

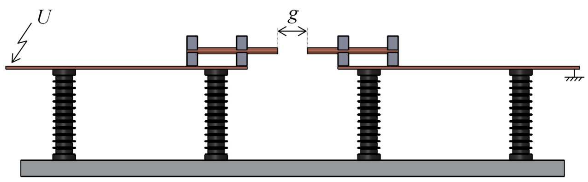
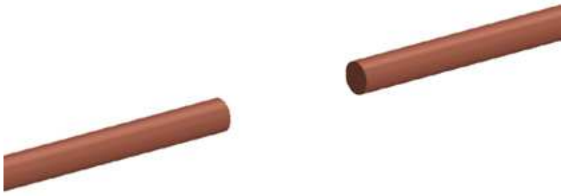


Fig. 1 Experimental setup for arc experiments in open air.



(a)

(b)

Fig. 2 Electrode arrangements for simulating stationary arc (a) and moving arc (b).

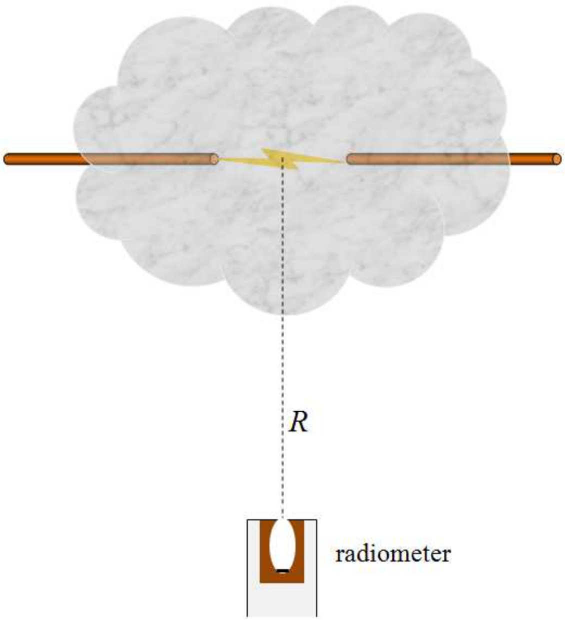


Fig. 3 A radiometer located at a distance R from the arc axis. The different parts of the figure are not to scale.

Radiation measurements: A heat flux transducer from Medtherm Corporation, mod 64LP-10F-20544 (series no 86603), was used for measurements of the thermal radiation from the arc cloud. Measurements were performed with the radiometer positioned normal to the arc axis, at different distances, *R*, to the arc, as seen in Fig. 3.

The radiometer worked as a thermocouple and generated a voltage signal based on the temperature difference between the thin membrane of the sensing surface and the massive copper at ambient temperature. The radiometer had a 63 % response time of 50 ms. The output voltage is directly proportional to the net heat transfer rate absorbed by the sensor.

Relative radiation energy: The registered voltage signal from the radiometer can be integrated over the entire arc duration. By assuming a spherical distribution, the radiation energy, W_{rad}, can be calculated by

$$W_{rad} = c_f \cdot 4\pi R^2 \cdot \int_0^t U_{osc}(t)dt \qquad (1)$$

where U_{osc} is the voltage signal from the radiometer measured with the oscilloscope, t is time and c_f is the calibration factor (0.8636 W/(cm^{2}mV) given from factory). The relative radiation energy can be found by dividing W_{rad} by the arc energy.

Frame subtraction method: A high speed digital camera, Fastcam SA3 model 60K-C1, was used for studying the cloud behaviour. Frame subtraction method was used to visualize the gas flow. The idea of the technique is basically to subtract one frame of the high speed video from the previous one, resulting in qualitative information of the density gradients [4].

3. RESULTS

Observations with high speed camera for the stationary arc burning between Cu-electrodes are reported in [5]. The arc was visible up to 0.3 s. Then a dark cloud of gas and particles formed around the arc and obscured the vision of the arc. The cloud was subjected to buoyancy and raised at 0.9 s and made the arc visible again. For the stationary arc burning between Al-electrodes, the arc was almost fully blocked by the cloud already after 0.1 s after arc ignition.

For the moving arc, the arc cloud formed was not as thick as for the stationary arc because of minimum electrode erosion in this case. The arc was visible on the high-speed camera throughout the entire arc duration.

Fig. 4 shows the smoothed voltage signal from the radiometer for five arc tests all with 5.1 kA test current. It can be seen that the radiometer measured radiation up to about 0.4 s after the arc is extinguished. This is partly because of the time-constant of the radiometer (50 ms), but mostly because the cloud formed around the arc was still hot and continued to emit radiation even after the arc itself was extinguished.

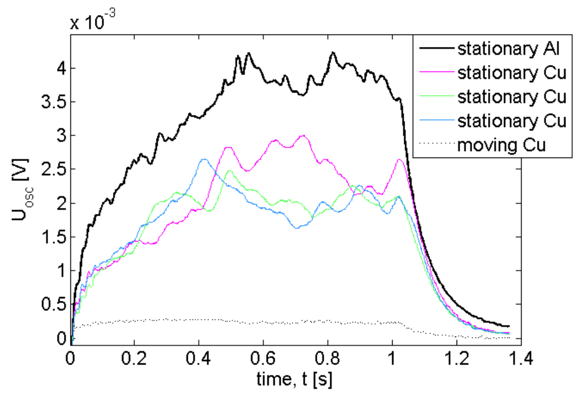


Fig. 4 Registered voltage signal from radiometer for different arcs with 5.1 kA test current. The radiometer was located 2.0 m away from the arc axis.

The three colored lines in Fig. 4 represent three identical tests with a stationary arc burning between Cu-electrodes with 100 mm gap. Three different regions can be distinguished in the graph during the arcing time:

1. First, the radiation voltage signal rises abruptly immediately after arc ignition.

2. From about 0.05 s, the signal rises steadily up to about 0.5 s. This rise is believed to represent the growth of the cloud, or the cloud formation time.

3. After 0.5 s the curves flatten, and despite some fluctuations, it seems like they have reached a more or less steady state where the energy input and output are in balance.

The steady rise seems somewhat steeper for Al-electrodes (black, solid line in Fig. 4) compared with the tests performed with Cu-electrodes, and the steady level provides a voltage signal about 1.5 mV higher than that for Cu.

For the moving arc, only the first and third regions can be distinguished in the dashed line in Fig. 4. After an initial, abrupt rise, the signal remains at an almost constant level throughout the remaining arc duration. The voltage signal is about 2 mV lower than the steady state of the stationary arc.

It appeared that the steady rise in the signal is in general slower and persists longer when the electrode gap decreases.

Spatial distribution: Three tests were performed with test current of 5.1 kA and 100 mm electrode gap, but with three different positions of the radiometer (5.0 m, 3.0 m, and 2.0 m). Calculating the total radiation energy by equation (1), the three tests varied only up to 2 % from the mean value.

Relative radiation energy: A general decrease in relative radiation energy was found for increasing electrode gap. An increase in relative energy measured as radiation was found for increasing test current. This is reported in [5].

Frame subtraction method: Fig. 5 is obtained by applying the frame subtraction method on one of the high-speed films. Black areas indicate no change between the two successive pictures.

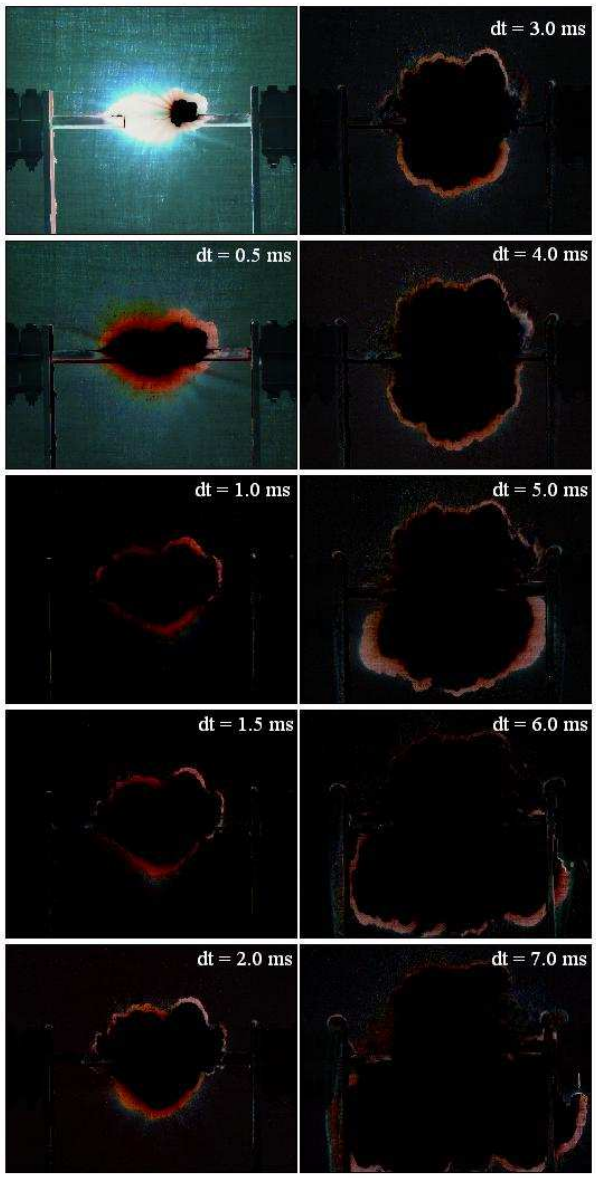


Fig. 5 Results after applying the frame subtraction method with 0.5 ms between subsequent pictures. Cu-electrodes with 100 mm gap and 5.1 kA test current. The times dt indicate time from first picture.

Fig. 5 shows that after 7 ms the cloud has developed its diameter to 40 cm. The cloud mean expansion speed can thus be calculated to about 30 m/s. No significant dependencies were found during this short time period on electrode material, gap and movement of the arc.

The radiation measurements indicated an arc cloud formation time of about 0.5 s before a steady state was reached (Fig. 4). To verify this by the frame subtraction method, a wider area around the arc should have been captured by the high-speed camera.

4. DISCUSSION

Reproducibility: Three tests were performed with the same test conditions, and the registered voltage signal from the radiometer for these tests followed each other closely (see colored lines in Fig. 4). Integrating these three voltage signals over the arc duration, the individual tests varied with up to 8 % from the mean value. The reproducibility of the radiation measurements between identical tests is thus regarded as acceptable.

Spatial distribution: A spherical expansion seems to be a reasonable assumption based on the low variation achieved for different values of *R*. No measurements with the radiometer at other angles were performed to support this assumption.

Electrode material: From Fig. 4 it was observed that the Al-electrodes gave higher measured radiation compared with the Cu-electrodes assuming that the calibration of the radiometer is the same for both arcs. The measured electrode erosion for Al was found to be enough to account for the difference in radiation due to different heat of combustion of the two materials.

Movement of the arc: The moving arc gave lower measured radiation (Fig. 4). An explanation might be that there is more energy transferred to the surroundings by convection and less metal vapour for the moving arc than for the stationary arc.

Electrode gap: A possible explanation for the decrease in relative radiation energy with increasing gap is that the arc column moves more with a larger gap, resulting in a higher fraction of the arc energy transported to the surroundings by convection. However, reservations should be taken with regard to the calibration factor and the spatial distribution.

A calibration of the radiometer was performed in a spherical oven, giving a calibration factor in the same order as the one given from factory. Since the geometry of the experimental setup reported in this study differ from the one used during calibration, some reservations should be taken with regard to the calibration factor used to obtain the radiation energies. Thus, additional work is required to obtain quantitative information regarding the radiation from the cloud.

Test current: An increase in relative energy measured as radiation was found for increasing test current. Here again, some reservations should be taken with regard to calibration and geometry, but a possible explanation might be that the spatial distribution is not spherical for higher currents (10 and 16 kA).

5. CONCLUSIONS

Electrode gap and test current was found to influence the formation of the arc cloud. Higher radiation was measured with Al-electrodes compared with Cu-electrodes. Lower radiation was measured for the moving arc compared to the stationary arc. Preliminary results with frame subtraction method indicate that this is a method which is useful when studying the arc cloud formation.

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