

DETERMINATION OF ELECTRIC CONDUCTIVITY OF HOT ARGON GAS USING A HIGH-FREQUENCY HIGH-VOLTAGE GENERATOR

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ABSTRACT

The paper describes a new method to determine the electrical conductivity of hot gas as well as plasma by evaluating phase shift between a high-frequency sinusoidal voltage and a corresponding sinusoidal current. The applicability of the new method is shown using an example of argon plasma torch. A sinusoidal high-voltage of several kV and a frequency in the range of several kHz is applied to electrodes (see figure 1). The conductive gas between the two electrodes results in a small capacitive-resistive current. Hence the electrode configuration can be regarded as a capacitor with resistor in parallel. The electrical conductivity is determined from the amplitudes and the phase shift between voltage and current using complex analysis. Measurements of gas pressure, at once allows a time dependence determination of the gas temperature.

1. INTRODUCTION

Determining the temperature in the direct ambience of an electric arc, for example in plasma- or switching arc technology are of fundamental interest. At conventional temperature measuring methods the temperature sensor has to place in the point of measurement and has to assume the temperature to be measured. Because of the heat capacity of the temperature sensor the measurement has always time delay. This effect is to prevent, for example by optical methods [1].

Subsequently, a novel measuring method is presented whereat the temperature of transient hot gas / plasma more than 1000 K between an electrode arrangement can be determined according to the pressure and the electrical

conductivity. Therefore a time varying voltage and the resulting current which corresponds to the electrical conductivity between an electrode arrangement (sensor) is used.

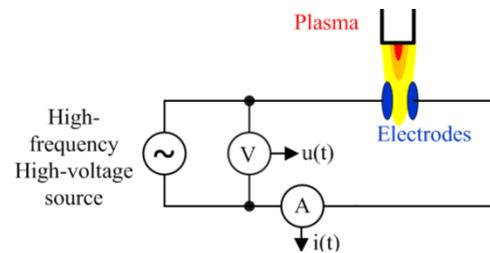


Fig. 1 Measurement circuit

Figure 1 shows the measuring circuit. For a high time resolution of the conductivity a high-frequency high-voltage power source is required. The alternating voltage and current are measured and the complex impedance of the electrode arrangement is calculated. With regard to the pressure at the measuring point a time resolved temperature can be determined with a sample rate of several kHz.

2. BASIC PRINCIPLE

The sensor is formed by a plate electrode arrangement. As an equivalent circuit a parallel connection of a resistor R and a capacitance C is given (see Fig. 2). From the amplitudes and the phase shift between the alternating voltage and current, the complex impedance can be derived for sinusoidal signals with the frequency f . If there is no hot gas or plasma between the electrodes, the resistance is very high, corresponding to a low conductivity of gas. The resistor can be neglected. Due to the high-frequency high-voltage a capacitive current is measured which can be calculated by equation (1).

$$\hat{I} = 2\pi f C \hat{U} \quad (1)$$

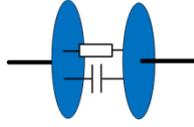


Fig. 2 RC-equivalent circuit of electrode-arrangement

If hot gas flows between the electrodes, the electrical conductivity increases and the resistance in the RC - equivalent circuit (see Figure 2) decreases. Hence, resistive and capacitive component of the total current changes. For the measurements, a sinusoidal voltage of 10 kV with a frequency of approximately 30 kHz was adjusted. The high-frequency high-voltage has two major advantages. First, it is ensured that a large capacitive current in the measuring circuit occurs (see equation (1)). Second, a high resolution in time of the electrical conductivity and therefore the temperature is only possible with a high frequency. For determining the time dependence of the electrical conductivity, each period of the measured current and voltage is evaluated and the electrical conductivity is calculated by complex calculation. The time resolution of the conductivity increases with the frequency of the source voltage. The determination of the electrical conductivity is limited by the measurability of the phase shift between current and voltage signal.

3. MATHEMATICAL DERIVATION

At a sinusoidal voltage with a frequency f applied to a parallel connection of resistor and capacitor the current is divided according to the ratio of resistance R and the capacitive reactance $2\pi fC$. This results in phase shift between current and voltage. With complex calculation the impedance of the parallel equivalent circuit is given by equation (2). The complex conjugated equation is given by equation (3) according to the basic form of equation (4).

$$\underline{Z} = \frac{\frac{R}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{R}{j\omega CR + 1} \quad (2)$$

$$\underline{Z} = \frac{R}{1 + \omega^2 C^2 R^2} - j \frac{\omega CR^2}{1 + \omega^2 C^2 R^2} \quad (3)$$

$$\underline{Z} = \text{Re}\{\underline{Z}\} - j \text{Im}\{\underline{Z}\} \quad (4)$$

Necessary parameters for calculating the impedance are derived from the measured voltage and current. These are the amplitudes of voltage \hat{U} and current \hat{I} , the phase shift φ_{ui} and

the frequency f . Then the complex impedance is given by equation (5). This equation follows also the basic form of equation (4), respectively equation (3). The real part is equation (6) and the imaginary part is equation (7). The solution of the linear system of equations is equation (8) for the resistance and equation (9) for the capacitance. The electrical conductivity κ is calculated by equation (8) using of the geometrical values, area A and distance l of the electrode arrangement, see equation (10).

$$\underline{Z} = \frac{\hat{U}}{\hat{I}} (\cos(-\varphi_{ui}) + j \sin(-\varphi_{ui})) \quad (5)$$

$$\text{Re}\{\underline{Z}\} = \frac{\hat{U}}{\hat{I}} \cos(-\varphi_{ui}) = \frac{R}{1 + \omega^2 C^2 R^2} \quad (6)$$

$$\text{Im}\{\underline{Z}\} = \frac{\hat{U}}{\hat{I}} \sin(-\varphi_{ui}) = \frac{\omega CR^2}{1 + \omega^2 C^2 R^2} \quad (7)$$

$$R = \frac{\text{Re}\{\underline{Z}\}^2 + \text{Im}\{\underline{Z}\}^2}{\text{Re}\{\underline{Z}\}} \quad (8)$$

$$C = \frac{\text{Im}\{\underline{Z}\}}{\omega (\text{Re}\{\underline{Z}\}^2 + \text{Im}\{\underline{Z}\}^2)} \quad (9)$$

$$\kappa = \frac{l}{RA} \quad (10)$$

4. GENERATION OF THE HIGH-FREQUENCY HIGH-VOLTAGE

For the generation of the high-frequency high-voltage a novel high-frequency high-voltage generator (herein after referred to as HFHV-generator) is used.



Fig. 3 High-frequency high-voltage generator, 1-inductive coupler, 2-low capacitive divider, 3-resonance converter

The HFHV-generator is shown in Figure 3 and is presented in [2]. Because of the resonant principle, the generated voltage is sinusoidal (see Fig. 4). As a function of the load, a sinusoidal voltage with maximum amplitude of 70 kV can be generated in the range of 1 kHz to 50 kHz.

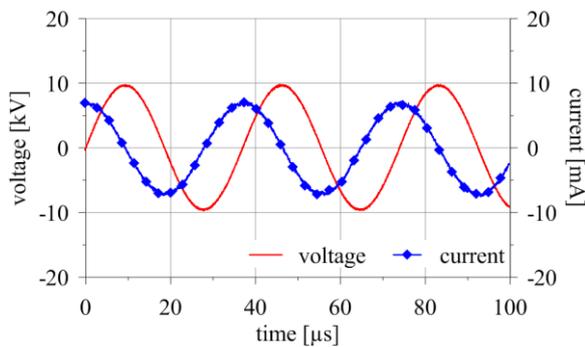


Fig. 4 Generated sinusoidal high-frequency high-voltage and corresponding current

5. MEASUREMENT OF VOLTAGE AND CURRENT

The high-frequency high-voltage is measured with a special low-capacitance low-loss high-voltage divider (see Fig. 3, 2). It has a constant divider ratio in the frequency range of the HFHV-generator. The electrodes are arranged coaxially and insulated by SF₆-gas, to avoid dielectric heating of the high-voltage capacitance. Thus during steady state operation, the divider ratio remains constant. The current measurement is carried out with a current transformer (Pearson principle). Due to the high-frequency of the source voltage, the resulting currents are in the range of several mA. The current transformer is specified for high resolution measurement of currents in the range of several mA at several kHz in steady state operation with a divider ratio of 1:10 (multiplier).

6. TEST SETUP AND TEST METHOD

The first tests of the novel measuring method are carried out with a DC plasma torch where argon is used as shielding gas. The aim is to study the measuring parameters during a plasma nozzle moves near the electrode arrangement and the hot gases flow through it. So the temperature and the electrical conductivity between the electrodes changes over time. Therefore a robot arm system is used where the plasma nozzle can be moved on a defined way with adjustable speed. Figure 5 shows the test setup at the plasma laboratory. For the measurements the sinusoidal high-frequency high-voltage is applied to the electrode arrangement. Then the plasma nozzle moved once-only vertically down and up again. Meanwhile voltage and current is measured and recorded continuously over the time.

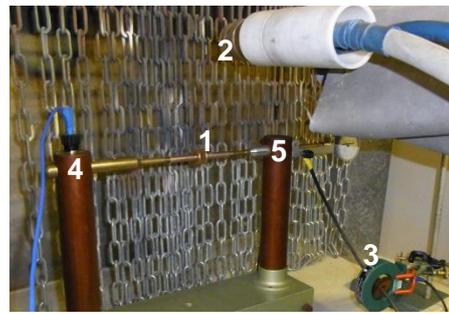


Fig. 5 Electrode-assembly, 1-electrodes with $\varnothing 20$ mm and 15 mm distance, 2-plasma-nozzle on robot arm, 3-pearson current-transformer, 4-high voltage connection, 5-earth connection

7. RESULTS

Figure 6 shows an example of the measured voltage and current during the plasma nozzle movement. The pictograms show the position of the plasma nozzle. Twice, downwards and upwards, the hot gas flows through the volume between the electrodes within 2 seconds. In the diagram it can be seen, that the amplitude of the voltage and hence the amplitude of the current is reduced, meanwhile the hot plasma flows through the electrodes. This is caused by the increasing conductivity and the fact that the voltage source is not automatically readjusted.

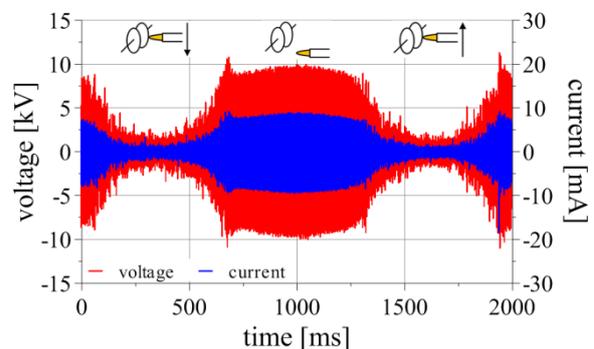


Fig. 6 Example of the measured voltage and current over time during the move of the plasma nozzle

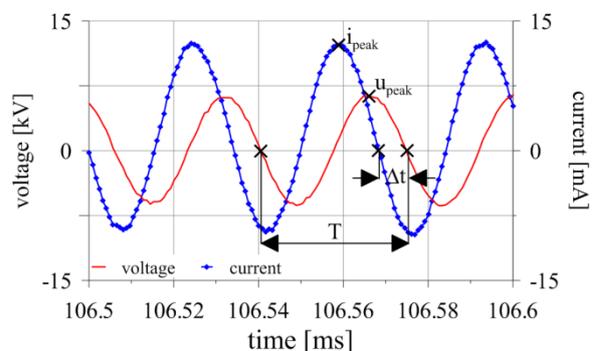


Fig. 7 Example of the measured voltage and current over time and values for electrical conductivity calculation

Figure 7 shows a few periods of the current through and the voltage across the electrode

arrangement at the moment where the hot gas flows through the electrodes. The relevant values to calculate the electrical conductivity for one period are marked in the diagram. Table 1 lists the measured values and the calculated electrical conductivity. It can be seen, that the phase shift between voltage and current is decreased from 90° (capacitive behavior) to 66.31° due to the increase of the electrical conductivity.

Table 1 Determined values according to Fig. 7

u_{peak} [kV]	6,327
i_{peak} [mA]	12,27
T [μs] / f [kHz]	34,1 / 29,239
Δt [μs] / ϕ [$^\circ$]	6,3 / 66,31
κ [$\mu\text{S/m}$]	23,804

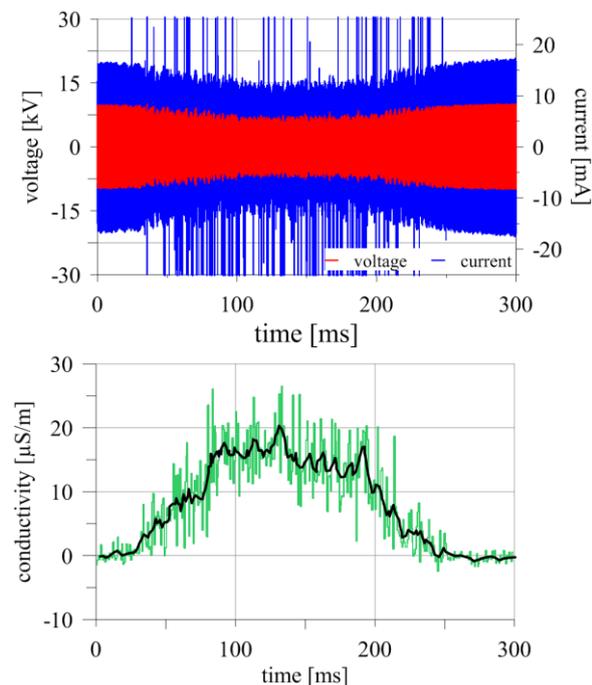


Fig. 8 Example of the measured voltage and current over time (top) and determined electric conductivity over time (bottom)

Figure 8 (top) shows a further diagram of recorded voltage and current meanwhile a downward moving of the plasma nozzle. Furthermore it can be seen that multiple breakdown of the hot gas between the electrodes occurs. In Figure 8 (bottom) the corresponding calculated time profile of the electrical conductivity is shown. The conductivity follows the time profile of voltage and current without any time lag. The electrical breakdown does not affect the generator and the measurement as long as the gap again reinforces. At the determined electrical conductivity of approximately $20 \mu\text{S/m}$ and ambient pressure of 1 bar Argon gas a temperature of about 2900 K is given [3]. The comparison with measurements of temperature

field around the stationary burning plasma using enthalpy-probe yielded good agreement. The measurement uncertainty is estimated about 100 K.

7. CONCLUSION

The paper describes a novel method for determining the electrical conductivity of hot gas in a volume between two electrodes with high resolution in time. Therefore a sinusoidal high-frequency high-voltage is applied to the electrodes. From the measured time characteristics of voltage and current, the complex impedance is evaluated in each period. Thus, a transient change of the electrical conductivity can be detected with a sample rate of several kHz. The sampling rate corresponds to the frequency of the applied voltage. If the gas pressure is measured additionally, the curve of a transient temperature change can be determined without any time lag. The limits of the measurement method will be determined by the measurability of the phase shift between current and voltage and the dielectric strength of the hot gas between the electrodes.

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