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CORONA AS A TEMPERATURE PROBE FOR ATMOSPHERIC AIR MICROWAVE PLASMA

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A new method for temperature measurements of near-LTE plasmas generated in air at atmospheric pressure was developed and tested. It is based on the combination of microwave and corona discharge. The gas temperature of the MW discharge is determined as the rotational temperature of N_2^* produced in the corona discharge. The temperature was measured by the corona probe method and the thermocouple simultaneously. We found a fairly good agreement between the two methods, with a slightly higher temperatures measured by the corona method. The difference (~100 K) is small relative to the measured plasma temperatures (close to or above 1000 K). This verifies that the corona probe method can be applied to determine the temperature of the near-LTE air plasma and contrary to the thermocouple it can be used also for the high plasma temperatures.

1. Introduction

Atmospheric pressure microwave (MW) plasmas present considerable interest for various industrial or environmental applications such as surface treatment [1], carbon nanotube synthesis [2,3], trace element analysis [4], air pollution control, various biomedical applications [5] etc. The main advantage of MW plasma is electrodeless operation, availability of cheap microwave sources at 2.45 GHz, good microwave to plasma energy coupling and no need of vacuum devices if the discharges are generated at atmospheric pressure. In addition, the operation of such plasmas is cheap, when operated in air.

In general it is very important to know the characteristics of the generated discharge in order to ensure its suitability for a desired application. Optical emission spectroscopy (OES) is a good, reliable and non-intrusive method of plasma diagnostics. It enables identification of active species and radicals in the plasma, as well as temperature measurements (vibrational and rotational temperatures). We introduce a novel temperature-diagnostic method of near equilibrium (near-LTE) air plasmas.

2. Corona probe method

The gas temperature T_g in the plasma, one of the key plasma parameters, can be determined by OES by comparing measured and simulated atomic and molecular emission spectra of the generated plasma. This method is very convenient but sometimes overestimates the temperature if emission spectra of radicals are considered. The radicals can gain energy in the chemical processes of their production, which can contribute to the elevated temperature. This phenomenon was observed by several authors [6,7, 8]. This implies that the best way to determine the plasma temperature by OES is to use the spectra of the particles that are a direct part of the feeding gas. In air plasma, the most convenient is to determine the gas temperature from N_2 spectra, since N_2 molecules are present in the feeding gas and are not produced by chemical processes in the plasma.

In discharges generated in air at atmospheric pressure, the emission of the first and second positive system of N_2 is usually observed. In near-LTE MW plasma generated in air, however, the excitation of N_2 takes place only at the temperatures above 6000 K [9]. Such high temperature is not reached in our plasma; therefore there is no N_2 emission. Furthermore there is even no (or too weak to detect) emission of NO, OH or O_2 that are usually present in LTE air plasmas. With no appropriate radiation it is not possible to perform OES temperature diagnostics of the generated air plasma.

However, it is known that N_2^* is produced in non-equilibrium air plasmas, e.g. in the corona discharge. In this strongly non-equilibrium discharge, T_g is low (close to room temperature) but the high temperature of electrons is sufficient for the excitation of N_2. In the discharges at atmospheric pressure, the rotational temperature balances with the temperature of the surrounding gas T_g. So we put corona discharge directly into the MW plasma. N_2^* is then produced by electron-impact excitation but its rotational temperature equilibrates with the surrounding gas temperature – in our case, the temperature of the MW plasma. The cold corona discharge (when operated in ambient air, T_g = 300±50 K) does not significantly contribute to the increase of T_g. By using the corona probe, i.e. by combining the MW plasma with corona discharge, we can determine the temperature of MW plasma (as the rotational temperature of N_2^*).

To test the reliability of this new corona probe method, we also measure the temperature by the thermocouple and the probe simultaneously and compare the two measurements. Use of thermocouples to measure the temperature of the plasma generated at low pressures and high temperatures is affected by the heat transfer processes and the method is considered not very reliable in this case. At atmospheric pressure in general, thermocouples can be used for temperature measurements if the gas temperature and the gas flow rate are not too high. It is also suitable to use the thermocouple with the smallest probe diameter possible so that it does not affect the gas flows and the discharge itself. In some cases, the thermocouple is placed in a ceramic tube to prevent the heat losses along the thermocouple wires and also to support the thermocouple in a desired position. Plasma temperature was measured by a thermocouple for example in [10-12].

3. Experimental setup

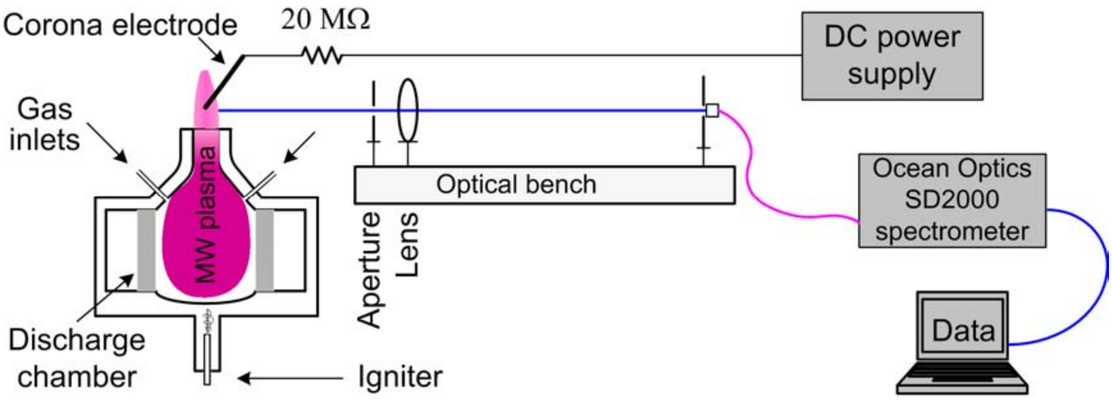

Fig. 1. Experimental set-up. Corona discharge combined with the MW plasma and OES diagnostics.

Litmas Red MW plasma torch powered by a 900 W magnetron, supplied from Richardson Electronics switching power generator SM1050, was used to generate atmospheric pressure air plasma with properties close to LTE. Microwaves generated by a magnetron are focused to the cylindrical plasma chamber made of a hardened teflon or Al_2O_3. A thin teflon tape is placed in the waveguide between the plasma chamber and magnetron to prevent the contamination of the magnetron or the resonant circulator by dust or gases which could cause its malfunction.

The MW discharge is ignited by pneumatic insertion of a metal igniter into the plasma chamber. The brush-shaped igniter (synchronized with microwaves from the magnetron through the electronic unit) causes a local enhancement of the electric field resulting in a discharge ignition. The whole system is externally cooled with water and air. Contrary to the typical MW torch systems, in our case the gas is inserted downstream and tangentially through the two holes of the nozzle into the cylindrical plasma chamber. This is causing the swirl flow in the cylinder and the generated swirling plasma is consequently blown out upstream through the central orifice of the nozzle. Blown-out plasma is then analyzed by optical emission spectroscopy. Emitted light is guided through the optical bench containing an aperture, a fused silica lens and optical fibre holder. Ocean Optics SD2000 spectrometer covering the spectral range of 200-1100 nm is used. The optical bench is movable horizontally and vertically. Experimental set-up and the basic torch characteristics are described in more detail in [13].

For the combination of MW plasma with the corona discharge (figures 1,2), the electrode and power supply for the corona were added.

We use a special 75 mm long hollow syringe needle with a diameter 0.9 mm as a corona electrode. It is very important to be able to get the spectra from the very exact point (the tip of the needle) where the corona discharge is applied. For this reason, the corona needle is placed in the micrometric movable holder which enables the vertical and horizontal movement.

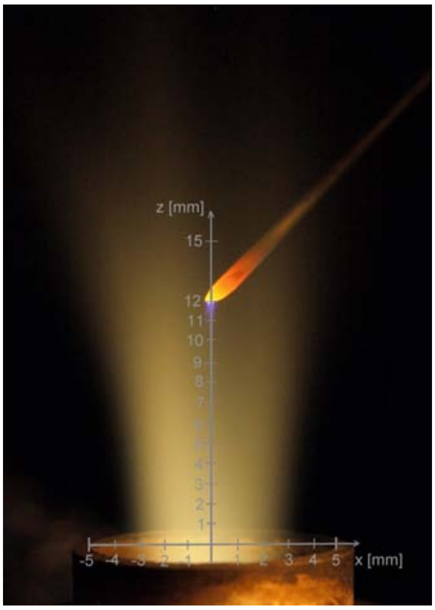

Fig. 2. Corona probe in the MW air plasma.

4. Results

We applied the corona discharge probe into the air MW plasma to measure its temperature. We determined Tg of the MW plasma as a rotational temperature of N_2 generated in the corona discharge. We used SPECAIR [14] for the spectral simulations that were then fitted to the measured spectra. The typical measured N_2 ($C^3\Pi_u$–$B^3\Pi_g$) spectrum is shown in figure 3.

By this method, we measured the temperature profiles (temperatures at various lateral positions x, i.e. distances from the vertical plasma axis) of the MW plasma at various conditions – power P and gas flow rate Q in various heights z. The maximum temperature was not found directly in the centre of the plasma (at the vertical z-axis) as expected but it was shifted to the side. This is a result of the plasma shape which depends on the gas flow conditions. At lower gas flow rates, the generated plasma has a symmetric conical shape and the maximum temperature is usually at (or very close to) the z-axis, which is the case of Q=5 l/min (figure 4).

With the higher gas flow rates, the shape of the plasma was not symmetric, because plasma was being strongly blown out. We would need to increase the power if the conical shape should be maintained but the magnetron power is quite low so in the case of Q=8 or 11 l/min (figure 5) it was not possible to maintain a stable conical-shaped plasma. We also measured the vertical temperature profiles (dependence on the height z above the nozzle). The results show that the temperature is mostly decreasing with z (figure 6).

To test the reliability of the corona probe method we measured the MW plasma T_g by the corona probe and the thermocouple simultaneously. This means that the thermocouple and the corona electrode were placed at the same movable holder and the holder was shifted during the measurement in such a way that either the corona electrode or the thermocouple was in the desired measuring position. The time delay between the corona probe and the thermocouple measurement was only a few seconds (untill the holder was moved from one position to another). During this time, the parameters of the plasma did not change significantly. These experiments were done at two various gas flow rates Q=5 and 8 l/min and constant power P=367 W. We measured the temperature profiles of the MW plasma in the height z=16 mm above the nozzle because it enabled us to measure the whole temperature profile. In the positions z<16 mm, the temperature (in the middle of the plasma, at x=0 mm) was above the thermocouple measuring range (max ~1300 K). In the positions z>16 mm, the N_2 emission was quite weak, especially at the sides of the plasma. The maximum temperature for Q=5 l/min measured by the corona probe was 1450±50 K and by the thermocouple 1350±20 K (figure 7). For the Q=8 l/min, the maximum temperature measured by the corona probe was 1180±50 K and by the thermocouple 1090±10 K (figure 8).

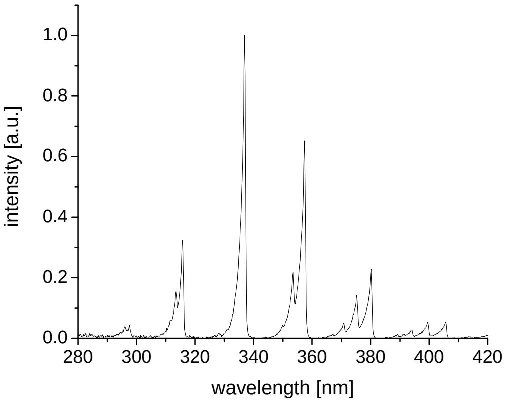

Fig. 3. Typical N_2 2nd positive spectrum measured by the corona probe in the MW air plasma with Q=5 l/min and P=368 W, DC corona 5 kV.

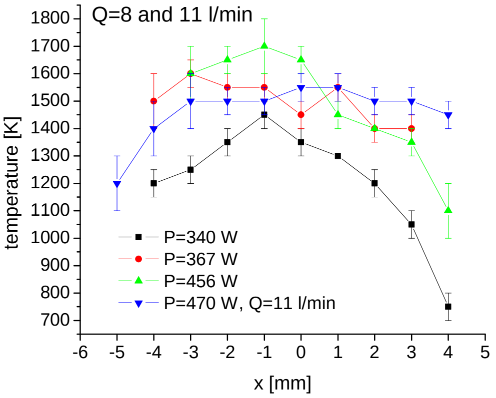

Fig. 5. The dependence of plasma temperature on the lateral position x in z=0 mm for Q=8 and 11 l/min.

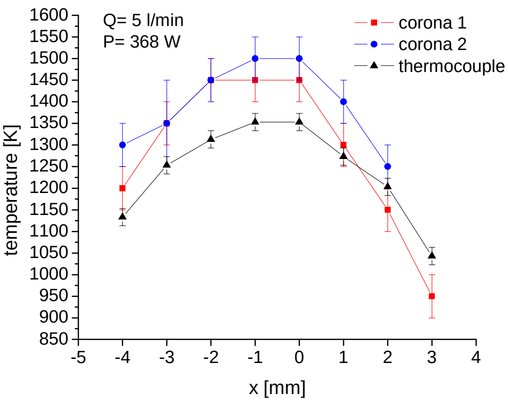

Fig. 7. The comparison of gas temperatures measured by the corona probe and the thermocouple at air flow 5 l/min and MW power 368 W. Corona1 and 2 were two sets of measurements.

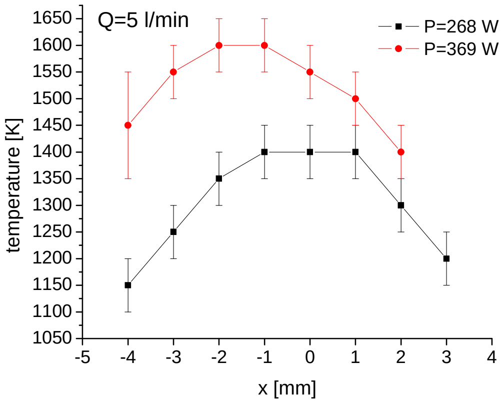

Fig. 4. The dependence of plasma temperature on the lateral position x in z=0 mm for Q=5 l/min.

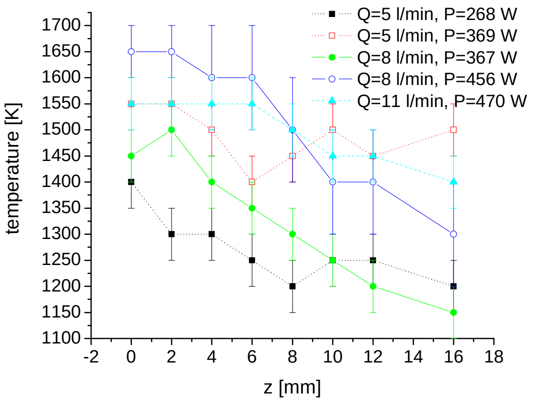

Fig. 6. The dependence of plasma temperature on the height z in x=0 mm at various operating conditions (P, Q).

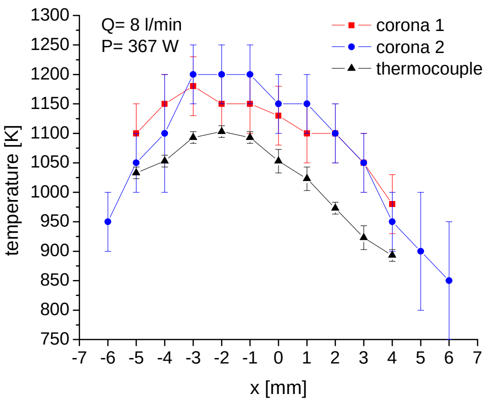

Fig. 8. The comparison of gas temperatures measured by the corona probe and the

thermocouple at air flow 8 l/min and MW power 367 W. Corona1 and 2 were two sets of measurements.

The results show that the temperatures measured by the corona method were slightly higher (up to 150 K) than the thermocouple temperature, but the difference is small relative to the measured plasma temperatures (T_g close to or above 1000 K). This verifies that the corona probe method can be applied to determine the temperature of the plasma and contrary to the thermocouple it can be used also for high plasma temperatures.

5. Summary

We developed and tested a novel diagnostics method of temperature measurements of near-LTE MW air plasma. A strongly non-equilibrium corona discharge applied inside the atmospheric pressure MW air plasma is used as an excitation source for N_2^* suitable for OES diagnostics. The gas temperature lateral and axial profiles of the MW plasma were measured. The comparison of the temperatures measured by the new method and the thermocouple showed a good agreement, with the temperatures measured by the corona probe slightly higher. Nevertheless, the corona probe can be applied even to higher temperature plasmas, out of the typical range of thermocouple use.

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