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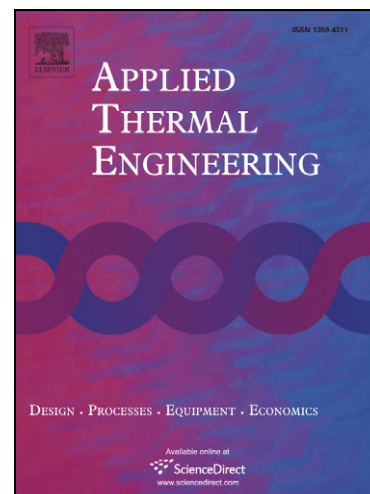
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Conduction heat transfer in a cylindrical dielectric barrier discharge reactor

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Abstract:

The thermal behaviour of a dielectric barrier discharge reactor is studied. The experimental tests are performed on a laboratory reactor with two working fluids: helium and air. A simple heat conduction model for calculating the heat loss is developed. By using temperature measurements in the internal and external electrodes, a thermal resistance of the reactor is defined. Finally, the percentage of the input power that is dissipated to the environment is given.

Keywords: DBD reactor, heat conduction, thermal resistance

Nomenclature:

| | | |
|-----------|--|---------------------------------------|
| p | generated power per unit volume | (W.m ⁻³) |
| P | total generated power | (W) |
| η | percentage of input power dissipated by heat conduction. | (%) |
| λ | thermal conductivity | (W.K ⁻¹ .m ⁻¹) |
| R_T | thermal resistance | (K.W ⁻¹) |
| R_G | thermal resistance of the annular gas gap | (K.W ⁻¹) |
| R_i | internal radius of DBD reactor | (m) |
| R_0 | internal radius of the glass tube | (m) |
| r | radius | (m) |
| L | length of the outer electrode | (m) |
| T_e | temperature at the surface of the internal electrode | (K) |
| T_o | temperature at the inner surface of the glass | (K) |
| T_{ex} | temperature at the outer surface | (K) |
| T_g | temperature of the gas in plasma zone | (K) |

1. Introduction

Dielectric barrier discharges (DBD) and corona discharges can be used to produce non-thermal plasmas at atmospheric pressure. Highly reactive species (ozone, excited atoms..) which are generated within such plasmas can be utilized in many applications such as deposition of coatings [1], reactive surface treatments [2] and pollution control [3]. In a DBD reactor, a dielectric material is placed in the discharge gap on at least one metal electrode; this leads to the formation of a large number of filamentary microdischarges of some nanoseconds duration. As a result, highly reactive non equilibrium conditions are obtained. Many experimental and numerical studies have clarified the fundamental processes of such microdischarge formation [4]. At atmospheric pressure, electron temperature is of order of a few eV (10000K) whereas gas temperature is considered to be nearly the ambient temperature. No much attempts have been made to understand the thermal phenomena in a DBD reactor due to the Joule heating of the gas. The main goal of this paper is therefore to develop a simple heat conduction model leading to the definition of a reactor thermal resistance. This model is then used to determine the heat losses in an experimental laboratory reactor with helium or air as working gases. Analysis according to the thermal resistance shows that 86% of the input power was dissipated to the environment when the flowing gas is helium and that this fraction falls to 42% in the case where air is the working fluid.

2. Experimental setup

2.1. DBD reactor

The experimental set-up is shown in Figures 1 and 2. The Dielectric Barrier Discharge reactor (DBD) used exhibits a coaxial geometry with a glass tube (12.4 mm in-diameter, 1.8 mm thickness) as dielectric barrier (Fig.2). The inner electrode, linked to the high voltage, is a 3.2 mm out-diameter steel tube. The outer electrode, connected to the ground, is a 1mm thick

and 80mm (L) long copper tube wrapped around the glass tube. The gap between both electrodes is 4.6 mm. The volume between electrodes in which occurs the discharge, called hereafter the plasma zone (Fig.2), is equal to 9 cm^3 .

Experiments were carried out at atmospheric pressure and in a room where the temperature is fixed to 20°C . The gases used are helium and reconstituted air (Purity $> 99,9\%$). The flow rate of gases was fixed to 116 ml/min (Brook mass flow controller). So, the residence time of gases in the plasma zone is 4.65 s .

In this reactor, no chemical reaction was observed with helium, whereas air leads to ozone and NO_x formation [2,5].

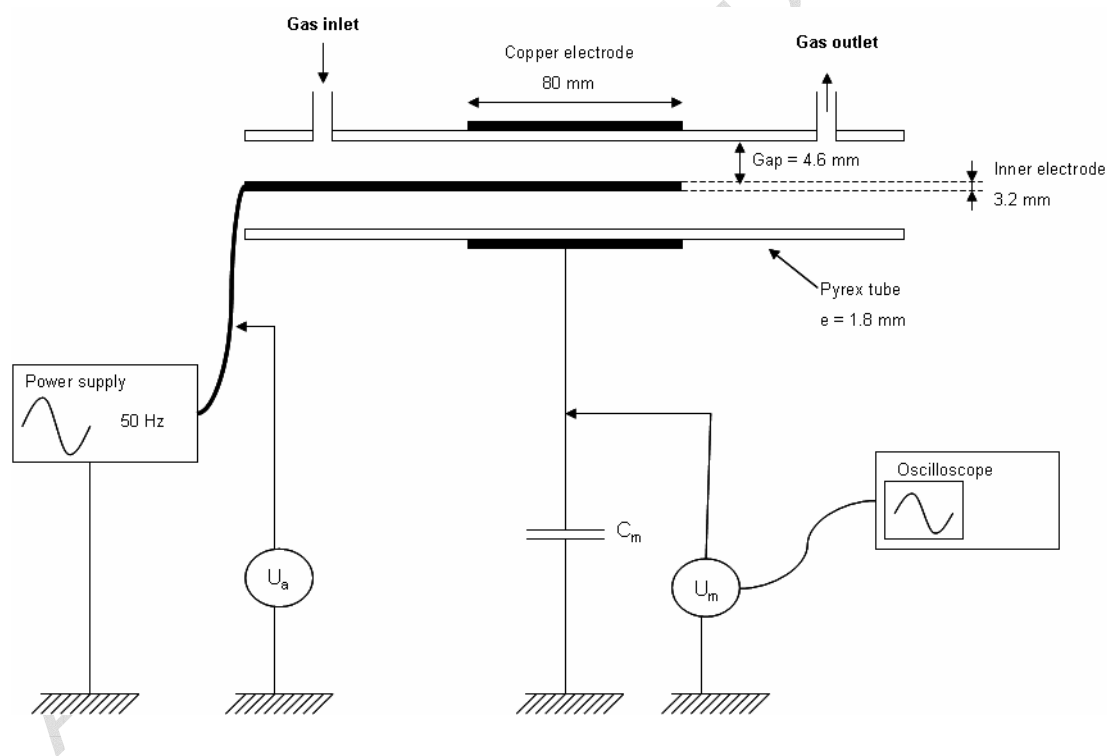


Figure 1. Experimental set-up.

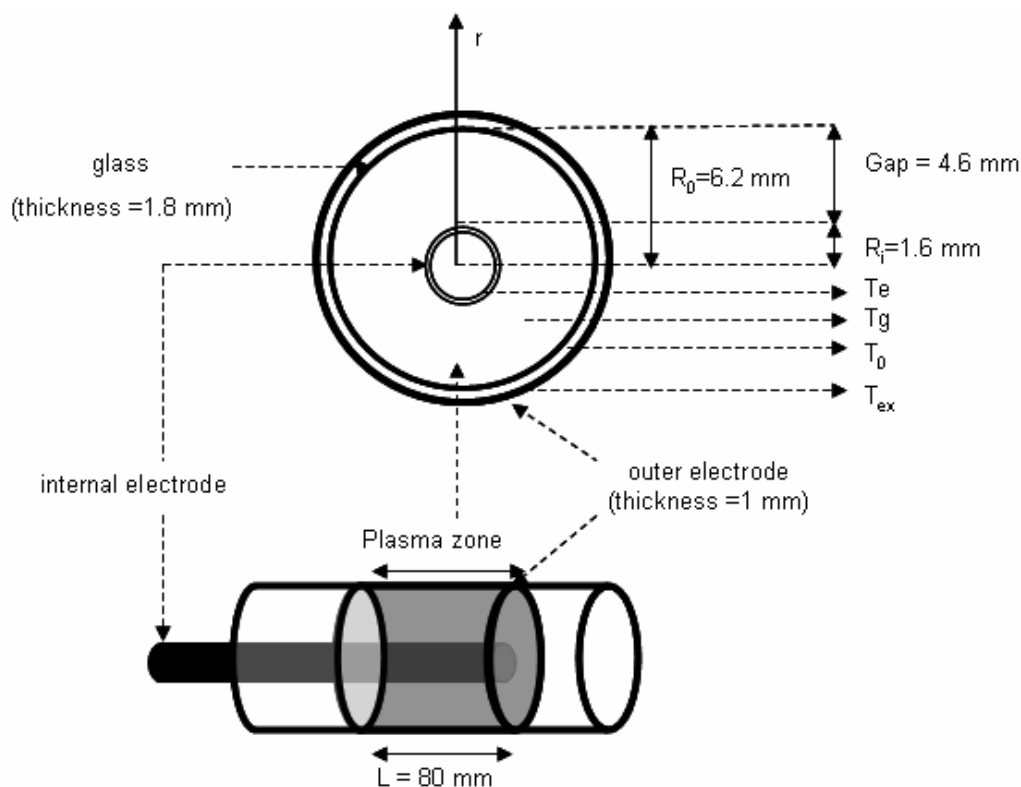


Figure 2. Scheme of DBD reactor with the positions of temperature measurements

2.2. Electrical Diagnostic

The electrical discharge was ignited by applying AC high voltage in the range 0 to 40 kV (peak to peak) with a frequency of 50 Hz (Fig.1). The charge Q (i.e. current integrated over time) was measured from the voltage (U_m) across a capacitor (C_m) of 560 pF connected in series to the ground electrode. The applied voltage (U_a) was measured with a high voltage probe (Lecroy, PPE, 20 kV, 100 MHz). The voltage and charge wave forms were recorded by a digital oscilloscope (Lecroy LT 374L) by averaging 256 scans. When plotting transported electrical charge Q as a function of the applied voltage (U_a), a typical discharge Lissajous figure is obtained the area of which gives the energy supplied during a period. The input power (P) injected in the DBD reactor was then calculated by multiplying the area by the frequency (50 Hz) and the capacitance.

2.3. Temperature measurement

In the plasma zone, any metallic device is subjected to electric arc. So, the use of thermocouples is not safe at all. Temperature measurements inside the plasma zone and the central electrode have thus been achieved with optical fibres. The measurements were recorded at a frequency of 0.5 Hz by means of a specific trade sensor, composed of an Y-bifurcated fiber provided with a gallium arsenide (GaAs) chip. Beyond 850 nm, gallium arsenide becomes optically transparent. The bandwidth of that component depends on temperature and varies by an amount of 0.4 nm/K. The position of the bandwidth, and therefore of temperature, is determined by the spectral detector integrated to the measurement box. Temperature of the outer electrode were measured by a Infra Red pyrometer thermometer (Raytech, MiniTemp MT4). Temperatures were recorded at different locations in the reactor. In this study, we focus on the temperatures of the internal (T_e) and the external (T_{ex}) electrodes (Fig 2).

2.4. Experimental results

For each power input in the DBD reactor, temperatures measured at different points increase with time and reach a steady state. Figure 3 shows that the steady state temperatures T_e and T_{ex} increase with the input power as expected whatever the gas used. For the same input power, it can be seen that the temperature levels are higher with air. These experimental steady temperatures will be used in the analytical model developed in the next section.

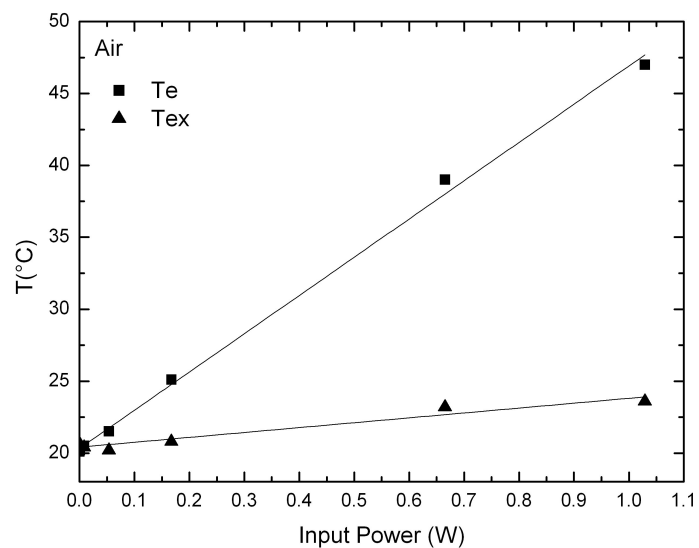
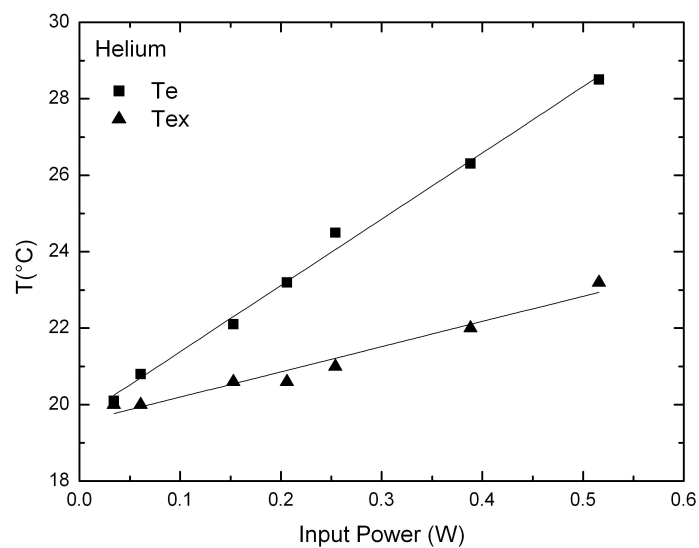


Figure 3. Temperature in the DBD reactor versus the input power with helium and air

3. Heat conduction model

In this section a simplified one dimensional heat conduction model is proposed. The convected heat flux by the flowing gas is neglected due to i) the low mass flow rate used in the experiments and ii) to the fact that the observed axial temperature variation is much lower than the radial temperature variation. We will thus assume that heat is generated in the plasma and that it flows radially to reach the external electrode where it is dissipated by convection and radiative transfer to the environment which is at an ambient temperature. One can of course calculate the heat losses by measuring the temperature of the external electrode and by using appropriate heat exchange coefficient h and emissivity of the surface. However, these parameters and the heat flow through the wire linking the external electrode to the ground are difficult to estimate. In order to avoid this problem, we have chosen to calculate the heat flux by using the measured temperatures at the two electrodes. Besides, this conduction model can also be used to predict the internal gas temperature and its variation in the radial direction.

3.1 Radial temperature

We consider the problem of heat conduction in the annular space enclosed between two coaxial cylinders described in section 2.1. The gap is filled with a gas in which heat is generated with a power per unit volume calculated in the annexe in the form:

$$p = \frac{A}{r^2} \quad (1)$$

Where r is the radial coordinate and A a constant which will be determined later.

The problem is thus governed by the following steady heat equation:

$$\frac{\lambda}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) = -\frac{A}{r^2} \quad (2)$$

where λ is the thermal conductivity of the fluid.

The solution is readily obtained as:

$$T(r) = -\frac{A}{2\lambda}(\ln r)^2 + C \ln r + D \quad (3)$$

The hollow internal electrode (of radius R_i) is very thin; we will thus neglect the heat flux flowing along the cross sectional area of this electrode and assume that the following boundary condition holds at the surface of the inner electrode:

$$\frac{dT}{dr} = 0 \quad \text{at} \quad r = R_i \quad (4)$$

This leads to the following expression for the constant C:

$$C = \frac{A}{\lambda} \ln R_i \quad (5)$$

The constant D is obtained by using the temperature T_e at the surface of the internal electrode:

$$D = T_e - \frac{A}{2\lambda}(\ln R_i)^2 \quad (6)$$

Finally, the radial variation of temperature is expressed as follows:

$$T = T_e - \frac{A}{2\lambda} \left[\ln\left(\frac{r}{R_i}\right) \right]^2 \quad (7)$$

We will now express the constant A by using the total generated power P in the plasma zone enclosed between internal and external radius R_i and R_o and of length L (length of the external electrode) by using the following relation:

$$\int_{R_i}^{R_o} 2\pi p r L dr = P \quad (8)$$

Therefore, one obtains:

$$A = \frac{P}{2\pi L \ln\left(\frac{R_o}{R_i}\right)} \quad (9)$$

It is worth mentioning here that P is the heat generated in the gas. It is thus a fraction of the total input power, the other fraction being used by the inelastic collisions.

3.2 Radial Heat loss

We now consider that the gas is enclosed by a glass tube and the external electrode. If the temperature at the outer surface is T_{ex} , the total amount of heat flow across this composite envelope can be written as :

$$P = \frac{T_o - T_{ex}}{R_T} \quad (10)$$

Where R_T is the thermal resistance of the composite envelope and where T_o is the temperature at the inner surface of the glass which writes:

$$T_o = T_e - \frac{A}{2\lambda} \left[\ln\left(\frac{R_o}{R_i}\right) \right]^2 \quad (11)$$

By using equations (9) and (11) we rewrite equation (10) as follows:

$$P = \frac{T_e - T_{ex} - \frac{A}{2\lambda} \ln\left(\frac{R_o}{R_i}\right)^2}{R_T} \quad (12)$$

Using the expression of A, this can be written:

$$P = \frac{T_e - T_{ex} - \frac{P}{4\pi\lambda L} \ln\left(\frac{R_o}{R_i}\right)}{R_T} \quad (13)$$

Rearranging the previous equation, one finally obtains:

$$P = \frac{T_e - T_{ex}}{R_T + \frac{1}{4\pi\lambda L} \ln\left(\frac{R_o}{R_i}\right)} \quad (14)$$

One can thus define a thermal resistance R_G of the annular gas gap as:

$$R_G = \frac{1}{4\pi\lambda L} \ln\left(\frac{R_o}{R_i}\right) \quad (15)$$

In many situations, the composite thermal resistance is small compared to the gas resistance.

One then can simply write:

$$P \approx \frac{T_e - T_{ex}}{\frac{1}{4\pi\lambda L} \ln\left(\frac{R_o}{R_i}\right)} \quad (16)$$

By measuring the temperatures of the internal and external electrodes, one can thus use equation (14) to find the heat loss by conduction.

4. Results

The calculated heat losses are presented on table 1 (He) and on table 2 (Air) together with the applied voltage, the total electric input power, the internal electrode (T_e) and external electrode (T_{ex}) temperatures. In the last column is given the percentage η of the total input power which is dissipated by heat conduction. It is seen, as expected, that the heat losses increase with increasing voltage and thus with increasing input power. The thermal conductivity of He (0.16W/m°C) being higher than that of air (0.025W/m°C), heat loss is greater with helium and consequently temperature levels are higher in air. The fraction of the input power that is dissipated decreases with the input power. This decrease is more pronounced in the case of helium for which η is higher than 86%. On the other hand, the fraction of the input power is smaller when air is the flowing gas and globally its variation with the input power is less pronounced. This is due to the development of chemical reactions in air. Therefore, a larger fraction of the input power is used by these chemical reactions and the heat generated by electron and ion collisions is much lower.

Table 1: Experimental results and calculated heat losses for Helium

| Voltage kV | Input power W | T_e °C | T_{ex} °C | Heat loss W | η % |
|---------------|------------------|-------------|----------------|----------------|-------------|
| 19.4 | 0.51 | 28.5 | 23.2 | 0.44 | 86 |
| 16.2 | 0.39 | 26.3 | 22.0 | 0.36 | 92 |
| 12.6 | 0.28 | 24.2 | 21.0 | 0.27 | 97 |

Table 2: Experimental results and calculated heat losses for Air

| Voltage kV | Input power W | Te °C | Tex °C | Heat loss W | η % |
|---------------|------------------|----------|-----------|----------------|-------------|
| 20.3 | 1.03 | 47.0 | 23.6 | 0.43 | 42 |
| 17.6 | 0.67 | 39.0 | 23.2 | 0.29 | 44 |
| 13.7 | 0.17 | 25.1 | 20.8 | 0.08 | 47 |

In order to calculate the gas temperature, one must remember that the total generated power P is equal to the total electric input power (given in table 1 and table 2) multiplied by the parameter η . One can then deduce constant A given by equation (9) and use measured values of internal electrode temperature to obtain the gas temperature by using equation (7). We will focus here in the excess temperature $\Delta T = T_g - T_a$ where T_g and T_a are gas and ambient temperature. We present on Fig. 4 and Fig.5, typical variations of ΔT for air and helium respectively. It can be seen that the temperature gradient is higher with air as expected. This is due to its lower thermal conductivity. Finally, we have compared measured gas temperatures at an adimensional radial temperature $r/R_i = 2.4$ to the theoretical values given by the model and found that the maximum error was lower than 5%. These results assess the correctness of the proposed simple model.

5. Conclusion

The heat generated in a DBD reactor by elastic collisions and which is lost by conduction across the gas layer and the composite envelope of the reactor has been calculated by a simplified model. On the basis of this conduction model a reactor thermal resistance is established. By using electrode temperatures measurements, it has been shown that the fraction of the input power that is dissipated depends highly on the gas nature and decreases with increasing input power. The percentage of the input power that is dissipated to the environment by convection and radiative transfer is within a range between 0.86 and 1 when

helium is the flowing gas. This percentage falls to a range between 0.42 and 0.47 in the case where air is the flowing gas. We believe that this kind of models can be useful for obtaining optimal thermal conditions and the percentage of the input power that is used by the chemical reactions. Finally, transient process can also be considered. Such an unsteady model is underway and will be published soon.

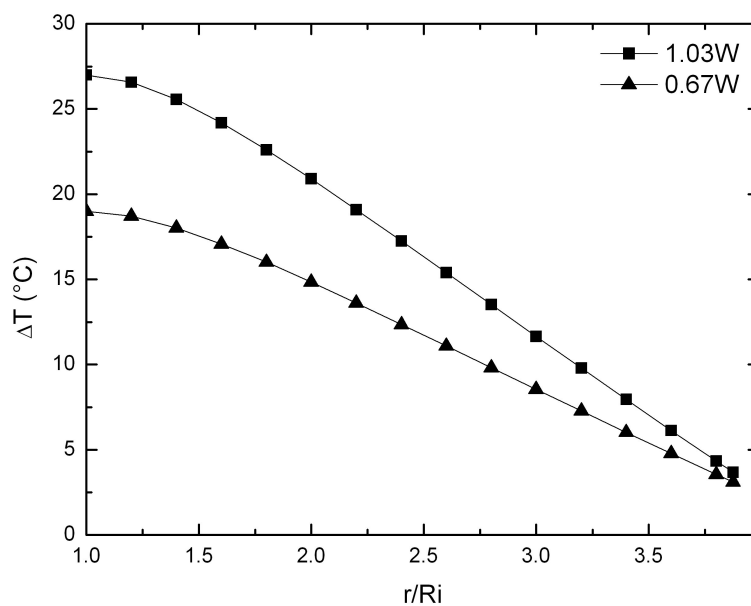


Figure. 4. Excess temperature with air for an electric power of 1.03 W (■) and P=0.67 W (▲)

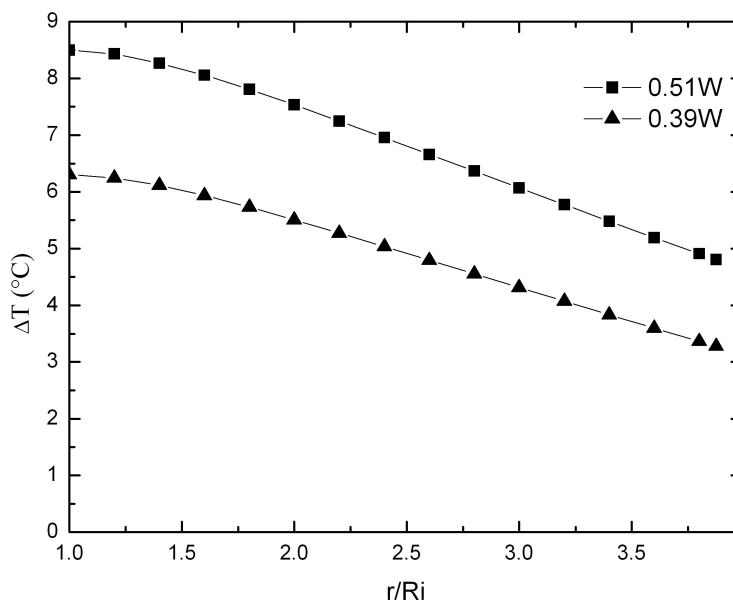


Figure.5. Excess temperature with helium for an electric power of 0.51 W (■) and P=0.39 W(▲)

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Annexe

Since net space charge is negligible in plasma, the governing equation for the voltage writes:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) = 0 \quad \text{A1}$$

The general evolution of the voltage is then given by:

$$V = C_1 \log(r) + C_2 \quad \text{A2}$$

Where C1 and C2 are constants of integration.

The electric field is obtained by taking the gradient of the voltage :

$$E = -\frac{\partial V}{\partial r} = -\frac{C_1}{r} \quad \text{A3}$$

Finally, the power per unit volume generated which is proportional to the square of the electric field is deduced as follows:

$$p = \frac{A}{r^2} \quad \text{A4}$$

Constant A will be determined by performing a heat balance.