Conference materials
UDC 533.9.08
DOI: https://doi.org/10.18721/JPM.161.174

Determination of discharge gas temperature with liquid non-metallic electrodes using the BOS method

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Abstract. Gas temperature is an important parameter in the study of atmospheric pressure plasma objects. The paper shows the possibility of determining the gas temperature of a discharge with liquid electrodes using the Background Oriented Schlieren (BOS) method. The discharge burns in an open air atmosphere between a liquid cathode and a metal anode. Tap water is used as the cathode, and a molybdenum rod is used as the anode. Based on the features of the BOS method and the geometry of the optical scheme, the main sources of errors are noted. The obtained temperatures are compared with the previously obtained results. It is shown that, taking into account the chosen geometry of the optical scheme, the results are in good agreement.

Keywords: background oriented schlieren, schlieren method, plasma diagnostics, non-equilibrium air plasma

Citation: Barinov Yu.A., Determination of discharge gas temperature with liquid non-metallic electrodes using the BOS method, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 433–437. DOI: https://doi.org/10.18721/JPM.161.174

Материалы конференции
УДК 533.9.08
DOI: https://doi.org/10.18721/JPM.161.174

Определение температуры газа разряда с жидкими неметаллическими электродами с помощью BOS метода

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Аннотация. Газовая температура — важный параметр при исследовании плазменных объектов атмосферного давления. В работе показана возможность определения газовой температуры разряда с жидкими электродами с помощью *фоново-ориентированного шлирен метода* (Background Oriented Schlieren – BOS). Исходя из особенностей BOS метода и геометрии оптической схемы, отмечены основные источники ошибок. Выполнено сравнение определенных температур с ранее полученными результатами. Показано, что с учетом выбранной геометрии оптической схемы результаты имеют хорошее согласие.

Ключевые слова: шлирен метод, диагностика плазмы, неравновесная плазма воздуха

Ссылка при цитировании: Баринов Ю.А. Определение температуры газа разряда с жидкими неметаллическими электродами с помощью BOS метода // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 433–437. DOI: https://doi.org/10.18721/JPM.161.174

Introduction

The heavy component temperature or gas temperature is an important parameter in the study of atmospheric pressure plasma objects. For example, for generators of low-temperature nonequilibrium plasma, the ratio of gas temperature to electron temperature is of interest. If the gas temperature reaches several thousand degrees, then non-contact methods, such as spectroscopic methods, are most often used for diagnostics. Among non-contact methods, the schlieren method can be noted. This method has been known for a long time, but due to difficulty of the organization, it is used mainly for the study of shock waves. Recently, because of the development of software and photo/video recording equipment, this method has received a new impetus. The new method is based on the principles of the schlieren method [1, 2], but due to computer processing of the obtained images, it has become much easier to the experiment organization. The new method has a well-established name Background Oriented Schlieren (BOS) method. To implement the method, the object under study is placed in front of the background screen. The background screen is, for example, a sheet of paper filled with dots. The rays reflected from the background screen pass through the object under study and are deflected under the action of density nonhomogeneity. This is registered as a background screen dot shift. The software used [3] determines the amount of shift. After that, using the geometry of the optical scheme, the deflection angle of the rays is calculated, and hence the refractive index of the medium n. In the case of neutral gas, such as air, the density has a simple relationship with the refractive index nair through the well-known Gladstone-Dale equation: n_{air}-1 = $G{\cdot}\rho$, where nair is the refractive index of air, G is the Gladstone-Dale constant, and ρ is the density of the medium. The constant G depends on the properties of the medium and the wavelength used. If the ideal gas law is satisfied for the object of study, it allows us to determine the temperature. The method is also applicable to the study of weakly ionized plasma. The contribution to the refractive index is made by both free and bound electrons. In this case, the effect of free electrons on the refractive index is much stronger. If the degree of ionization is not too high (< 0.001), then this influence can be neglected. If the discharge burns in air atmosphere, then various NO, OH, etc. radicals, O, H atoms, and also water vapor can be present in the plasma. Significant concentrations of these particles can affect the refractive index.

In [4, 5], the possibility of using the BOS method to determine the temperature of the discharge gas with liquid non-metallic electrodes was considered. This discharge in various configurations was studied earlier [6–8] The gas temperature was determined using spectroscopic methods. It is of interest to determine the temperature by an alternative method. In this paper, an attempt was made to determine the gas temperature using the BOS method.

Experimental setup

Discharge configuration with liquid cathode and metal anode is selected. The anode is a molybdenum rod 3 mm in diameter. The cathode is tap water. To avoid water overheating, a small duct is organized in the anode tank. The discharge burns in open air atmosphere. A photograph of the discharge is shown in Fig. 1.

In this configuration, the discharge has axial symmetry, which makes it possible to use the inverse Abel transform in processing [5]. In Fig. 2 the optical scheme of the experimental setup is shown.

The discharge is powered through a ballast resistance from a DC source with an adjustable output voltage of up to 4000 V. The discharge current can vary over a wide range from 20 mA to 200 mA. The experiment was carried out at a fixed current of 60 mA and an interelectrode gap of 6—7 mm. The image was recorded by a camera with a matrix size of 17.3×13 mm^2 and a lens with a focal length of. The 150 mm minimum focusing distance for this lens is 900 mm. A background screen with a regular arrangement of dots (background patterns) was used. Such a background screen simplifies image computer processing. The background screen was illuminated by a flash. Distance A = 745 mm, B = 187 mm.

Data treatment

The resulting images were processed by a developed python program. The program was written specifically for this experiment. At the moment, there are several programs for image processing

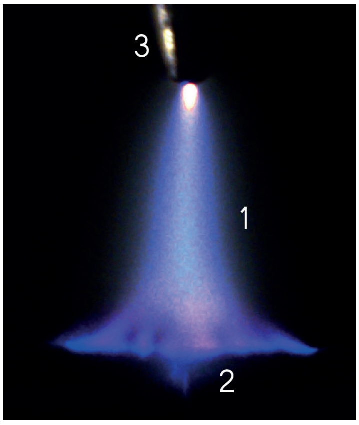

Fig. 1. Photo of discharge with a metal anode and a cathode from tap water in a stationary air atmosphere. 1 — discharge, 2 — water cathode, 3 — metal anode

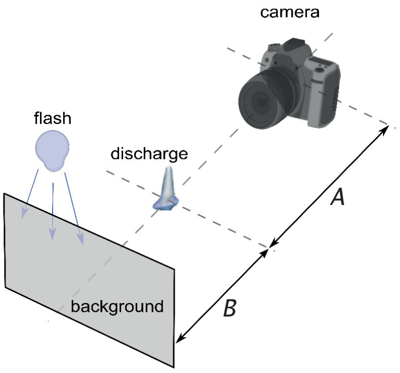

Fig. 2. Optical scheme of the experimental setup, $A = 745$ mm, $B = 187$ mm

using the BOS method, the most famous of them is PIVLAB [9]. As shown by preliminary studies [4, 5] for the chosen geometry, these programs can give a noticeable error. The developed program uses a different method for shift calculating and allows you to control the processing process.

Let us consider the main sources of errors. This, as it was found in [4], is blurring of the point contour. Disturbance of the axial symmetry of the plasma channel caused by convection and instability of the surface of the water electrode. Insufficient spatial resolution, due to the peculiarities of the BOS method. Since the camera focuses on the background screen, and not on the study object. It can also be noted the weak dependence of the refractive index on temperature at high temperatures of the medium (more than 1500 K). For processing, a region approximately 1–1.5 mm above the water electrode was cut out from the obtained images. The area close by to the water electrode, due to the presence of water vapor, has a noticeable effect on the refractive index, which leads to a distortion of the temperature profile. The treatment area was divided into 6 equal sections of ≈ 0.8 mm size. The temperature was calculated for each area. To minimize the processing error, the experiment was repeated many times. The most symmetrical ones were selected from the data set. The point shift contour obtained at the first processing step was divided into two halves, and then the halves were processed independently. Fig. 3 shows a typical view of the point shift contour. The obtained data were filtered, distant points were removed, and smoothing was performed.

As a result, the variation of temperature along the radius was calculated. The calculation is described in more detail in [5]. An example of the calculation result for the middle of the interelectrode gap is shown in Fig. 4.

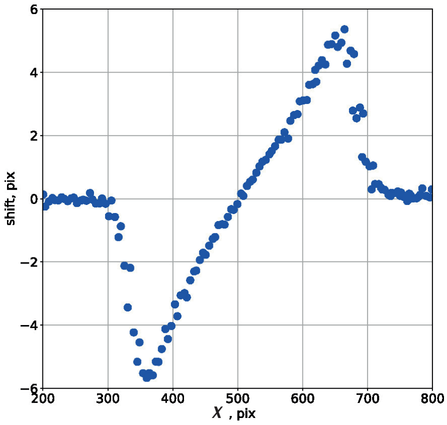

Fig. 3. Point shift contour

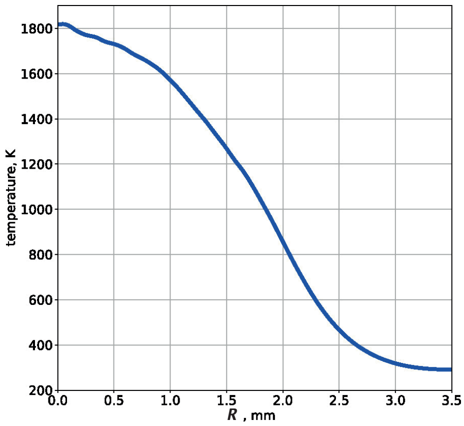

Fig. 4. Radial temperature distribution

It can be seen that the maximum temperature is reached on the discharge axis. It should be noted that due to insufficient spatial resolution, the values of spatial coordinates should be considered as approximate. An estimate of the spatial resolution gives a value of about 0.7–0.8 mm. Temperature calculations were performed for six sections of the interelectrode gap (Fig. 5).

The result of the temperature distribution in the interelectrode gap on the discharge axis is shown in Fig. 6. Starting from the cathode, the temperature rises slightly, and then slowly drops towards the anode.

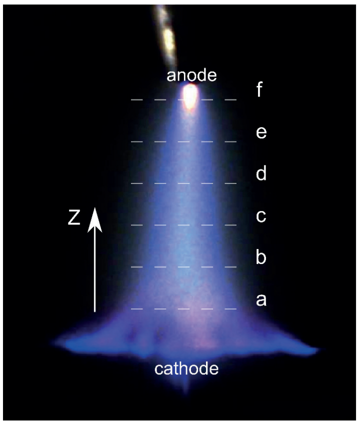

Fig. 5. Photo of discharge with measurement points

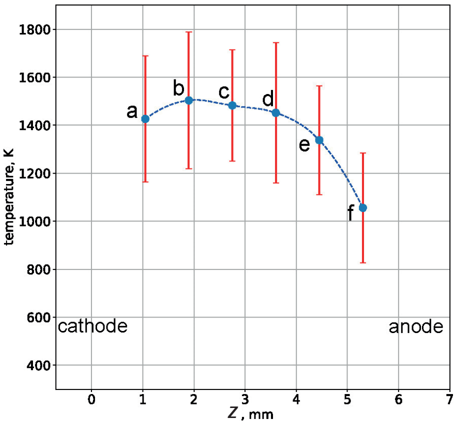

Fig. 6. Temperature distribution in the interelectrode gap

Conclusion

Let us compare the obtained temperature values with the results obtained using spectroscopic methods. In [6], the gas temperature of the discharge with liquid nonmetallic electrodes was determined. The temperature on the discharge axis reached a value of 2000 K. This value is noticeably higher than the value obtained in this work. This can be explained by the low spatial resolution. In [10], it was shown that the brightest region is on the axis of the discharge. At currents of 100–300 mA, the area has a diameter of 0.7–0.9 mm. This area can be considered the highest temperature. Thus, a rather narrow region on the discharge axis is averaged with the neighboring region where the temperature is lower, which results in a lower overall temperature. In view of the foregoing, the result obtained is in good agreement with experiment [6]. In the future, it is planned to carry out measurements with high currents. In addition, one can try to improve the spatial resolution by deconvolution of the result with a hardware function. The BOS method is interesting for its simplicity of organization and at the same time it allows obtaining not only qualitative, but also quantitative results. At the same time, depending on the geometry of the optical scheme, there may be problems with spatial resolution. Since this is a feature of the BOS method, unfortunately this influence can not always be minimized.

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Received 25.10.2022. Approved after reviewing 08.11.2022. Accepted 08.11.2022.