International Journal of Heat and Mass Transfer 60 (2013) 17–21

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Shadow photometric method for measurements of electron density in erosion plasma

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ARTICLE INFO

Article history:
Received 20 December 2012
Accepted 22 December 2012
Available online 20 January 2013

Keywords:
Plasma
Accelerator
Discharge
Shadow method

ABSTRACT

The purpose of this work is property investigation of quasi-stationary plasma formations with high energy content for practical applications in high thermal physics and diagnostic of materials under extreme conditions. Investigated plasma formations are the result of two plasma counter-flows interaction process which is based on high-current discharges of plasma accelerators of erosion type in vacuum. Shadowgraphs of colliding plasma flows were made using knife and slit method. As a light source a specially made argon flash lamp was used. Averaged electron concentration in the interaction area was calculated from intensity distribution of shadowgraphs. In order to perform a correct shadow display a light filter system with transmission peak at 547 nm was mounted in front of the CCD-camera. At this wavelength the relative intensity in plasma spectrum was low while in argon lamp spectrum it was near-maximum.

1. Introduction

At present a close attention is paid to the development of physical and technical concepts of making new plasma systems to obtain highly concentrated energy flows for photochemistry, high-temperature thermal physics, new material synthesis, and to use them as the base for new technologies and technological processes aimed at the modification of the material properties in extreme regimes of action [1–4]. The investigation of physical processes of interaction between plasma flows can help in solving a variety of actual scientific and industrial problems in quantum electronics, radiation plasma dynamics, diagnostic of materials under extreme conditions, etc. [5–10]. When colliding, the accelerated plasma flows may open up certain possibilities in producing new plasma formations [11–13].

For quantitative shadow studies of transparent inhomogeneities widely used photometric shadow techniques [14]. Shadow diagnosis of the brightly glowing plasma is very difficult by the fact that for shadow images we need to use a brighter light source than the investigated plasma. For these purposes, such light sources as a capillary discharge in argon, exploding wires, various flash lamp and pulsed lasers are used [15].

2. The method of the calculation of the free electrons density in the plasma

To calculate the light path in the optical inhomogeneity a rectangular coordinate system is used and positioned so that the z axis is oriented along the probe radiation, y axis along the plasma flows and the x axis is directed vertically. Assuming that the deflection of light in the inhomogeneity is small, we can neglect the curvature of the light path in it, and assume that the beam propagates straight, deviating very little from the path by which he would have gone in the absence of heterogeneity.

Under these assumptions, the Euler equations can be represented as [14,15]:

$$\begin{aligned} \mathrm{tg}\varepsilon_x &\approx \int_{z_1}^{z_2} \frac{d\{\ln[n(x,y,z)]\}dz}{dx}, \\ \mathrm{tg}\varepsilon_y &\approx \int_{z_1}^{z_2} \frac{d\{\ln[n(x,y,z)]\}dz}{dy}. \end{aligned} \tag{1}$$

The slit in the illuminating part was set horizontally, and it may be assumed thereby that the shadow device is sensitive only to deviations of light leading to a vertical displacement of the slit image. So, the value $\partial n/\partial y$ can be ignored, that is the dependence of the refractive index on y coordinate is ignored (the light beam is confined to any section $y = \text{const}$).

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.12.043

Nomenclature

ε_x	x-projection of light deflection angles	ξ	slit width of the shadow device illuminating part
ε_y	y-projection of light deflection angles	R	radius of inhomogeneity section by the plane y = const
z_1	coordinate of entrance point of light beam into optical inhomogeneity	λ	probe radiation wavelength
z_2	coordinate of exit point of light beam from optical inhomogeneity	e	electron charge
n	refraction coefficient of medium	N_e	electron density in plasma
n_0	refractive index of undisturbed medium	m_e	electron mass
I	shadow pattern intensity	c	speed of light in free space
I_0	shadow pattern intensity in absence of optical inhomogeneities	ΔN_e	electron concentration change
F	focal length of the objective of the shadow device detecting part	Δx_l	thickness of plasma layer
		Δz	optical path length of probe radiation in investigated inhomogeneity
		ε_s	angular sensitivity of shadow devise

Investigation of axisymmetric inhomogeneity is easier in a cylindrical coordinate system. In the transition to it from the rectangular coordinate system the Eq. (1) are transformed into an integral equation of Abel type [16,17]:

$$\varepsilon_x = \frac{2}{n_0}\int_x^R \frac{\partial n}{\partial r}\frac{x}{\sqrt{r^2-x^2}}dr. \tag{2}$$

The value of ε_x can be positive or negative, it is experimentally measurable and is obtained from the results of photometric measurements of the shadow patterns of plasma flows collision with the use of the formula

$$I(x,y) = \frac{1}{2}I_0 + \frac{\varepsilon_x F}{\xi}I_0. \tag{3}$$

For practical application of Eq. (2) Abel integral must be brought to the form solved for the derivative $\partial n/\partial r$. Multiplying Eq. (2) on $1/\sqrt{x^2-r^2}$ and integrating them over x^2, after simple transformations we obtain

$$\frac{1}{r}\frac{\partial n}{\partial r} = \frac{1}{\pi}\left[\frac{\frac{\varepsilon_x(R)}{R}}{\sqrt{R^2-r^2}} - \int_r^R \frac{\frac{\partial}{\partial x}\left(\frac{\varepsilon_x(x)}{x}\right)}{\sqrt{x^2-r^2}}dx\right]. \tag{4}$$

Assuming that the light beam passing through the optical inhomogeneity is not deflected at the point $x = R$, Eq. (4) can be written as

$$\frac{1}{r}\frac{\partial n}{\partial r} = -\frac{1}{\pi}\int_r^R \frac{\frac{\partial}{\partial x}\left(\frac{\varepsilon_x(x)}{x}\right)}{\sqrt{x^2-r^2}}dx. \tag{5}$$

By re-integrating this equation we find

$$n(x) = n_0 - \frac{n_0}{\pi}\int_r^R \frac{\varepsilon_x(x)}{\sqrt{x^2-r^2}}dx. \tag{6}$$

The density of free electrons in the plasma is determined from the relation [14,18]

$$n = 1 - \frac{\lambda^2 e^2 N_e}{2m_e c^2}. \tag{7}$$

3. Experimental setup

General scheme of the experimental facility is shown in Fig. 1.

Investigated interaction process is based on high-current discharges of plasma accelerators (1) of erosion type in vacuum. An end erosion plasma accelerator is a system of two coaxial copper electrodes separated by a caprolone insulator. An outer copper electrode is shaped as a convergent nozzle. The accelerators were mounted in a vacuum chamber (2) by means of copper co-axial current supply. Each accelerator was put into operation by discharging a capacitor battery. Shadow measurements were performed on an IAB-451 shadow device (3) using knife and slit method. The focal length of the detecting part objective is F = 1917 mm at a diameter of the observed field of 200 mm. The width of the slit in the illuminating part of the instrument was equal to ξ = 0.2 mm. The slit was placed horizontally. For the shadow images that are suitable not only for qualitative but also for quantitative interpretation the light source based on a pulsed spark discharge in argon was created (4), which allows to obtain a light pulse with duration of 3 μs (at the level 0.7 of maximum light intensity). A lamp operating voltage is 20 kV.

In the illuminating part of the device system of light filters (5) having a light transmission maximum at the wavelength λ = 547 nm was placed. For the shadow photograph of luminous plasma taken we must be sure that the plasma emission is not detected by the camera, while the radiation from the light source has been registered. For this purpose were selected light filters with a bandwidth at a wavelength at which the relative intensity in the spectrum of the plasma is small, and the relative intensity of the discharge spectrum of the light source is close to maximum (Fig. 2).

4. Results and discussion

The process of the interaction of plasma flows was recorded by PCO DICAM PRO digital hi-speed camera with an exposure time 5 μs. The results of high-speed photography reproducing the dynamics of the plasma flows collision process are shown in Fig. 3. The time specified above the pictures is the time interval from accelerators start to beginning of exposure.

In the early stages of the forming of quasi-stationary plasma formations the determining factors are the processes of large-scale turbulence (Fig. 3 – 5 μs), then in the areas of plasma flows compression are observed the formations of localized regions with high free electron density (Fig. 3 – 10 μs). After 15 μs from the beginning of the accelerators work region of increased electron density is moving to the central area between the accelerators and stable localized plasma spherical formation in centre of which electron density reaches its maximum value of $8.4 \cdot 10^{16}$ cm^{-3} for the investigated process forms (Fig. 3 – 15 μs). After 20 μs from accelerators start decrease of free electron density and the reduction of the geometric dimensions of the generated plasma formation are observed.

5. Shadow method sensitivity and data error estimation

Shadow method sensitivity in geometrical optics approximation, when flat optical inhomogeneity is being investigated, can be determined from relation [14]