Electrical and spectral energy measurement techniques of pulsed continuous spectrum radiation sources

S G Kireev¹, S G Shashkovskiy¹ and K A Tumashevich¹,²
¹ Scientific and Industrial Enterprise "Melitta", Ltd., Moscow, Russia
² FSBI Bauman Moscow State Technical University (National Research University of Technology), Moscow, Russia

E-mail: kireevsg.melitta@gmail.com

Abstract. The techniques of total spectral energy and electrical measurements of high-current pulsed arc discharge are presented and substantiated. On the example of a flash lamp, three working circuits were reviewed and the following values were obtained: time dependences for circuit electrical parameters, values of the energy deposition into plasma, and radiative efficiencies for different spectral ranges.

1. Introduction

A high-current pulsed arc discharge initiated in inert gas allows the gas in the lamp to be briefly heated to a temperature of above 12,000 K and to obtain a set of radiation parameters such as high intensity and continuous radiation spectrum in the range from the lamp envelope transmittance limit (150-170 nm) to near IR (1.1-1.3 μm). The combination of these parameters attracts interest in various fields: medicine and food industry [1, 2], water purification from organic pollutants [3], optical ranging, and powerful searchlight systems [4].

Increased interest in pulsed radiation sources (RS) actualized the task of developing diagnostic methods for determining both electrical discharge parameters and radiative ones. A sufficient number of instrument and methods of measurement [5, 6] are developed to determine the energy-power parameters of high-current pulsed discharges of short duration, while the determination of radiation energy still causes difficulties and leads to significant errors.

Widely used methods of radiation research of constant-flux lamps: photoelectric, based on internal or external photoelectric effect; photochemical, when changing the optical or physical properties of the substance is directly proportional to the number of absorbed photons; pyroelectric – due to appearance of electric field in the crystal, which is proportional to the change in its temperature – work on a similar principle with respect to monochromatic radiation. Pre-calibration of the radiation receiver at the wavelength of interest allows obtaining the proportionality coefficient between the irradiation of the photosensitive surface and the reaction to it. Subsequent measurements of lamps, mainly neglecting the spectral lines broadening, are the account of the obtained coefficient, area of the irradiated surface, solid angle and distance between the source and the radiation receiver.

This principle in the measurement of pulse sources with continuous spectrum radiation imposes additional requirements: high response speed and accounting of light source spectral distribution.
Nowadays there is no deficit in high-speed measuring devices, but the problem of accounting for the complex spectral composition of the radiation has not yet received sufficient attention.

A spectrometer as radiation receiver allows registering the light source spectral distribution due to software manufacturers accounting of the spectral sensitivity of the photodetector matrix and, with proper operation of integration time, makes it possible to record the radiation of a single pulse. Disadvantages are: optical-geometric matching of the device with a light source, which occurs due to limited viewing angle of the spectrometer, and calibration problems, caused by complexity of selection of standard RS.

The authors of the article [7] used a set of monochromator and pyroelectric sensor as a measuring system. Sequentially isolating spectral regions of 10 nm width, the receiving area of the pyroelectric sensor was irradiated. The obtained values allowed to construct the emission spectrum of the flash lamp. However, a comparison with the relative spectral distribution obtained by the spectrometer showed a noticeable difference, which can be explained not only by the rough measurement step, but also, apparently, by the lack of consideration of sensor spectral sensitivity variability. Thus, the sensitivity variation for most Ophir sensors is about 30-40% in the wavelength range of 200...1000 nm.

The technique, tested in the article [8], has shown a fundamentally new approach to the measurement of flash lamp radiation due to the system of a coaxial photocell FEK-22SPU and a spectrometer. The conversion factor is obtained by taking into account the spectral sensitivity of FEK-22SPU on the relative spectral distribution registered by the spectrometer. Thus, the authors were able to obtain the absolute spectrum of radiation in the spectrometric device registration range. The only significant drawback of this technique is the selected photocell which is difficult to calibrate by constant-flux light sources, and as a consequence has a high error value. The total error of the method was ≈ 18%.

Using a photodiode with an integrator circuit we managed to eliminate the shortcomings of the photocell FEK-22SPU. The simplicity and reliability of calibration by a constant-flux light source with an error of ≈ 5%, as well as low cost and availability of such photodetectors allows us to consider the proposed technique [9] as an alternative to existing ones.

2. Experimental setup and experimental procedure

The object of the study was a xenon flash lamp (FL) with arc length of 120 mm and internal diameter of 5 mm, filled with spectrally pure xenon.

For experimental studies of electrical and radiation characteristics of the lamp a test bench was assembled, whose circuit diagram is shown in figure 1. Power supply charged capacitor \( C_0 \) to a voltage \( U \). Initiation of the discharge was carried out using a high-voltage pulse with amplitude of ≈ 24 kV. The inductance and resistance of the circuit were ≈ 16 \( \mu \)H and 60 m\( \Omega \), respectively. The studies were conducted on three discharge circuits:

- \( 1 - C_0 = 10 \, \mu \text{F}, \, U = 1.54 \, \text{kV} \);
- \( 2 - C_0 = 30 \, \mu \text{F}, \, U = 1.43 \, \text{kV} \);
- \( 3 - C_0 = 120 \, \mu \text{F}, \, U = 1.38 \, \text{kV} \).

Discharge current was recorded using a calibrated coaxial noninductive current shunt SDN-001 with a minimum signal rise time of 30 ns and a resistance of 1.012 m\( \Omega \), which is 3 orders lower in magnitude than the resistance of the plasma channel. The shunt was located between the capacitor and trigger coil, which allowed excluding the influence of high-voltage pulse of discharge initialization to the oscillogram of discharge current.

The voltage drop was recorded both on the discharge gap of the lamp and on the capacitor by using three mixed type low-inductive voltage dividers Pintek HVP-39Pro with a rise time of ~ 2 ns. The first voltage divider was installed between the capacitor plates, the second and third by their high-voltage terminals were attached to lamp electrodes, and by ground terminals to the negative capacitor plate. obtained time dependences of the voltage drop from the second and third voltage dividers were subtracted from each other, resulting in time characteristic of the voltage drop on the lamp.
Figure 1. Schematic diagram of the diagnostic measuring bench
PS – power supply, VD1, VD2, VD3 – voltage dividers, C0 – storage capacitor,
Sh - non-inductive current shunt, Tc – trigger coil, FL – flash lamp, O1, O2 –
oscilloscopes, NB – notebook.

Signals from the current shunt and all voltage dividers were simultaneously output to the 4-channel oscilloscope TDS2024C.

Further oscillograms processing implied calculation of pulse power transferred to the circuit and the lamp by multiplying corresponding oscillograms of current and voltage, and calculating electric energy in the circuit and the lamp, obtained by power integration.

Spectral energy diagnostics was carried out by combination of photodiode radiometer (FR) UV Sensor "TOCON-C6", detecting irradiation in 240-270 nm range (at half-height) with maximum spectral sensitivity at 257 nm and back-thinned type CCD spectrometer with high quantum efficiency and high UV sensitivity “AvaSpec-ULS2048-USB2”, detecting irradiation in the 200-400 nm range. FR pre-calibration was carried out to obtain the spectral distribution of relative sensitivity normalized to its maximum value and the absolute volt sensitivity value at the wavelength of maximum sensitivity.

Measurement of the total radiation energy was carried out by using calibrated a black-body (0.19-20 µm) pyroelectric detector Ophir PE50BB-DIF with most constant spectral sensitivity in the entire range.

The essence of the technique [9] is mathematical calculation of the spectral composition of radiation, which comes to FR (Figure 2), and subsequent calculation of the conversion factor for the data obtained by the spectrometer:

\[ K_{sp} = \frac{U_{FR} \cdot \tau \cdot \left( S_{max} \cdot \int_{\lambda_1}^{\lambda_2} E_{sp}(\lambda) \cdot S(\lambda) d\lambda \right)^{-1}}{\lambda} \]

where \( K_{sp} \) denotes the coefficient of proportionality for the spectrometer in J/rel.unit, \( U_{FR} \) the signal at RC-circuit output in V, \( \tau \) the RC time constant in s, \( S_{max} \) the volt sensitivity at wavelength of maximum sensitivity in V·m²/W, \( E_{sp}(\lambda) \) the reaction of the spectrometer to incoming spectral distribution of energy radiation, rel.unit/(m²·nm), \( S(\lambda) \) the FR spectral sensitivity normalized to its maximum value in rel.unit, \( \lambda \) the wavelength in nm, \( \lambda_1 \) and \( \lambda_2 \) are the wavelength ranges within the spectral sensitivity of FR.
Figure 2. Relative spectral energy distribution with FR sensitivity

Figure 3. Spectral energy distribution of the flash lamp

3. Experimental testing of the technique
For all studied modes, time dependences of power characteristics were obtained, graphically shown in Figure 4. The shape of current in all considered modes was aperiodic with maximum values from 415 to 1012 A and the time of its reaching was from 25 to 66 µs. Such values indicate high brightness of plasma radiation. Black-body temperature estimation in the FR spectral range gives values of 6.8, 7.5 and 8.5 kK for modes 1-3, respectively.

Figure 4. Discharge circuit power parameters at $U_C = 1.38$ kV, $C = 120$ µF.
$P$ – discharge current; $U_C$ – capacitor voltage; $U_{FL}$ – lamp voltage; $P_C$ – circuit power, $P_{FL}$ – lamp electric power; $P_C$ – circuit electric power; $W_{FL}$ – lamp electric energy, $W_C$ – circuit electric energy.
Attention is drawn to the shift in time required to reach the maximum electric power dissipated in the circuit, compared with the power in the lamp. This fact is explained by presence of significant inductance in the discharge circuit due to used toroidal trigger coil, as well as the nonlinear nature of plasma resistance. The efficiency of energy deposition into plasma calculated as ratio of energies dissipated in the lamp and the circuits was above 90% for all modes, which indicates good matching of circuits with the lamp and a relatively small value of total resistance in all circuits.

Studying the discharge radiation characteristics made it possible to obtain the spectral distribution of radiation in absolute units and to calculate the radiation energy in different ranges within the field of spectrometer sensitivity. For example, for circuit 1, the radiation energy in 200-300 nm range, the most relevant in the field of disinfection by UV radiation, was 0.4 J, which is equivalent to 5% of the total emitted energy, and for circuit 3 – 5.2 J and 6.3%, respectively. The increase of radiation efficiency in the UV region is due to black-body temperature rising with energy input expansion.

Table 1. Power and radiation parameters of the pulsed xenon lamp in studied circuits

| Parameter                                    | Studied circuit |
|----------------------------------------------|-----------------|
| Maximum discharge current I, A               | 415             |
| Time to peak current τ_m, µs                 | 25              |
| Lamp peak electric power P_{FL}, kW         | 272             |
| Energy input characteristic time τ_{0.35}, µs | 35              |
| Electrical energy dissipated in the circuit W_C, J | 11.4           |
| Electrical energy dissipated in the lamp W_{FL}, J | 10.7           |
| Efficiency of energy input to plasma η_pl, % | 90              |
| Radiation energy in the range of 200-300 nm W_{200-300}, J | 0.4            |
| Total radiated energy W_R, J                | 7.9             |
| Radiation efficiency η_r, %                 | 67              |

Figure 5. Radiated spectral energy distribution by flash lamp. Where 1, 2, 3 – experimental circuits
4. Conclusion
In this study were performed electrical measurements of pulsed high-current discharges in xenon, which allowed calculating the power parameters of the circuit and the plasma in FL. The developed method of radiation measurement technique allows calculating radiation energy in any part of the spectral range of the spectrometer with accuracy of 8%.

The set of described techniques allows not only to calculate, but also to optimize the efficiency of a pulse light source in selected spectral ranges depending on the discharge circuit parameters. Data on spectral distribution and absolute values of radiation energy allows to predict the effect in various fields of application.

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