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REMOTE MONITORING OF RADIATION TEST TEMPERATURE REGIME AT A HIGH-CURRENT ELECTRON ACCELERATOR

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Methods for evaluating the radiation resistance of structural materials of nuclear reactors have been developed and research is being carried out in NSC KIPT. As a part of these studies, a supercritical water convection loop with a chamber for irradiation of the tested samples by electron beam of the accelerator LU-10 (beam energy of 8…10 MeV, beam power up to 10 kW) was developed. A pyrometric system based on a DSLR camera (Digital Single-Lens Reflex Camera) has been created for the remote continuous non-intrusive control of the surface temperature of the irradiation cell in the range of 350…550°C. The work presents the results of calibration and use of the developed system in the conditions of a 500-hour run of sample irradiation in the loop.

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INTRODUCTION

In the contemporary radiation technological processes, the electron beams with average power of tens and hundreds of kilowatts are widely used [1]. Such radiation sources are also used in the radiation tests, in particular, of the actual and promising materials of nuclear reactors [2].

In recent years, the problem of increasing the efficiency of nuclear power plants, in particular, due to the use of new efficient coolants, has become of high importance. Water in a supercritical state is considered as one of the most promising heat carriers [3]. Work on the development of methodology and equipment for assessing the stability of materials intended for SCWR reactors (The Supercritical Water-Cooled Reactor) is being carried out at the National Science Center of KIPT. The supercritical water convection loop with a chamber for irradiation of test materials, developed at KIPT and installed at the output of a LU-10 electron accelerator (beam energy 8...10 MeV, beam power up to 10 kW), makes it possible to conduct research on their corrosion and mechanical damage in a regime corresponding the operating conditions of the SCWR reactors [4].

The action of high-power radiation fields on objects is accompanied by their heating by tens and hundreds of degrees. At the same time, along with the absorbed dose, the temperature of the samples is a parameter that affects the result of their irradiation. On the other hand, the temperature control in radiation processes represents a certain difficulty. The most promising are the non-contact measurement methods based on registration of the object's own thermal radiation. In particular, continuous remote monitoring of its temperature can be provided by optical pyrometry techniques. Photo- and video cameras with CCD matrices are commonly used for such measurements [5, 6]. An additional problem is the presence in the area of measurements of scattered bremsstrahlung radiation, which is formed during the interaction of accelerated electrons with the elements of the output devices of the accelerator, as well as the impact on the measuring devices of electromagnetic radiation, which is generated by pulse systems of the accelerator power supply. All the listed circumstances were taken into account during elaboration of the temperature measuring channel.

1. DEVELOPMENT OF A SYSTEM FOR REMOTE TEMPERATURE CONTROL

Radiation protection of measuring equipment is necessary for stable registration of the object's own thermal radiation. This can be achieved by moving it away from the region of the beam interaction with an irradiated object. When analyzing the conditions of such measurements, it is also necessary to evaluate the contribution of the luminescent component, which can affect the accuracy of temperature determination. Taking into account these conditions, the registration scheme was developed (Fig. 1).

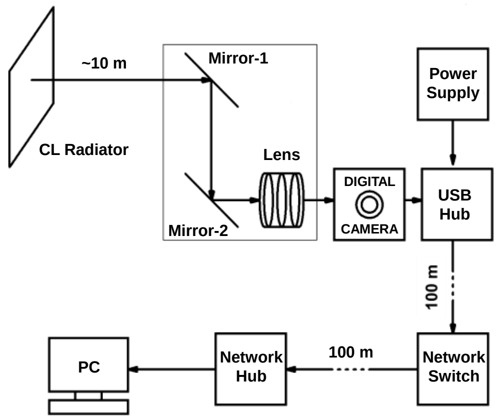


Fig. 1. Functional scheme of the system for recording the thermal radiation of objects under the action of a LU-10 electron beam

Compared to the previously created pyrometric system [7], the new development is distinguished by an increased range of measurements and greater accuracy. This is ensured by the use of a camera image sensor with larger working plane and better optical lenses.

The system includes a remote-controlled Canon EOS XT digital camera, the working range of which is extended to the near-infrared region [8], a specially designed optical path, a USB-TCP interface converter, a communication line, and also a personal computer with appropriate software.

2. A STUDY OF THE CAMERA SENSOR RESPONSE

A stand was created to determine the characteristics of the camera image sensor response. It consists of: an adjustable source of stable current, a light-emitting diode with color temperature of 4100 K, a light diffuser, and also the camera itself under PC control. Fig. 2 shows the measured light signal characteristics of the camera sensor.

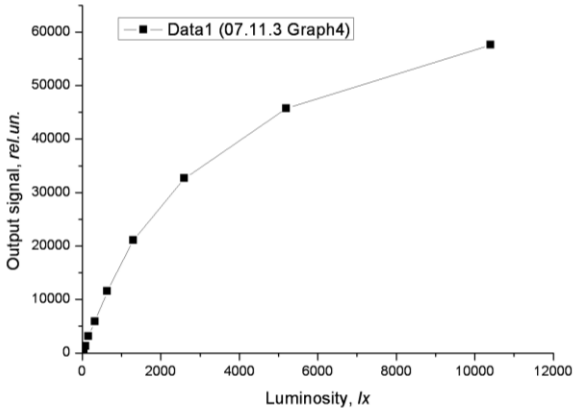


Fig. 2. Light signal characteristics of the Canon EOS XT image sensor

Shooting with the camera was carried out in a manual mode with fixed current through the light-emitting diode. The light sensitivity and aperture of the camera were also fixed, only the shutter speed was changed. Illuminance was calculated by formula:

$$E = \frac{A^2 \cdot 250}{S \cdot t}, \quad (1)$$

where A is the aperture; t is the exposure period in seconds; S is the light sensitivity (in ISO units); E is the illuminance in lux; k=250 is the calibration constant of the incident light meter when measured with a flat light receiver [9].

The magnitude of the output signal in conventional units was determined during image processing by a software package. Fig. 3 shows the linear part of the obtained characteristic. It can be seen that its length takes about one fourth of the entire scale.

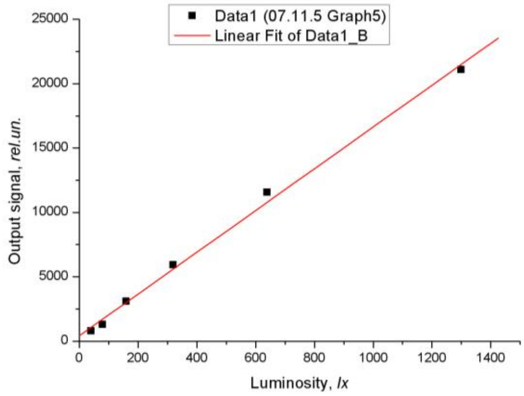


Fig. 3. The working range of the Canon EOS XT DSLR image sensor response

3. CALIBRATION OF THE TEMPERATURE MEASURING CHANNEL

The dependence of intensity of the thermal radiation of a sample on temperature (the light-temperature characteristic) was previously investigated on a stand, the schematic of which is shown in Fig. 4. A tested sample Rh1 was made of the same material, that was later used in an irradiation cell of the supercritical water convection loop. The sample was heated with an electric current regulated with an autotransformer Tr1. The temperature was measured with a "TERA" digital thermometer using a chromel-alumel thermocouple fixed in the middle of the sample.

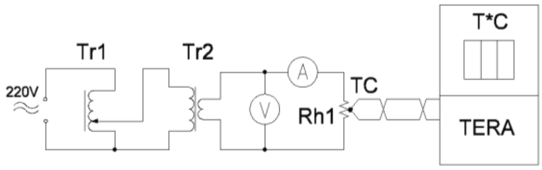


Fig. 4. Schematic diagram of the stand for researching the emissivity of the studied samples

Calibration of the measuring channel was carried out in a completely darkened room. Initial camera parameters in manual adjustment mode were:

- the aperture (did not change), A = 5.6;
- the shutter speed varied in the range 1…1/8 s;
- the sensitivity, ISO.un., varied in the range 1600…100.

The camera was connected to a PC via the USB-HUB port and controlled remotely using Canon's Remote Shooting utility.

The beginning of the glow of the sample was registered at a temperature of 340°C. The survey was carried out approximately every 10°C at the time of setting the readings of the "TERA" temperature meter. The intensity of thermal radiation in relative units was determined at the point of attachment of the thermocouple to the sample (Fig. 5).

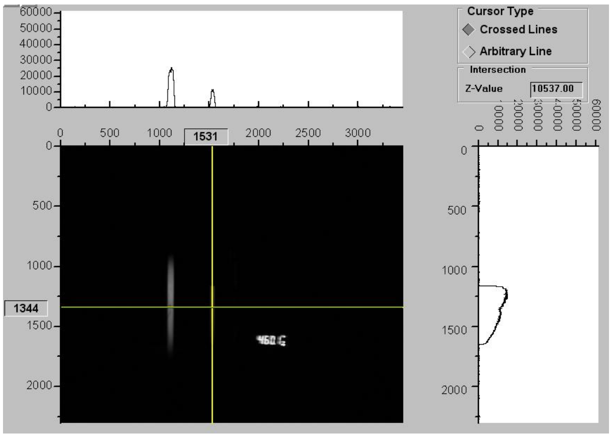
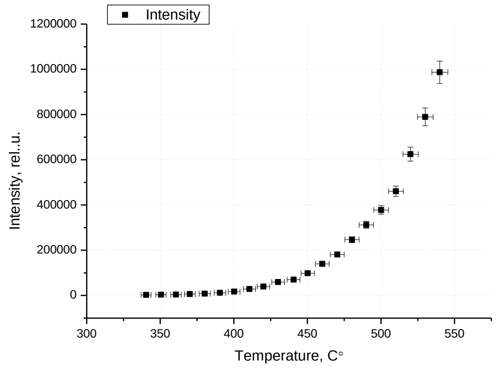


Fig. 5. Distribution of the intensity of thermal radiation (relative units) of a sample heated with an electric current up to 460°C at the point of attachment of the thermocouple (right)

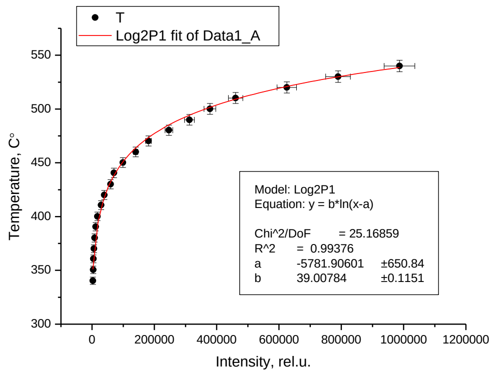
To extend the range of measured temperatures during sample heating, the exposure was appropriately adjusted to not exceed the linear part of the camera sensor's response.

Fig. 6,a shows the obtained dependence of the intensity of thermal radiation of the sample on the temperature in the range from 340 to 540°C. The calibration curve for solving the inverse problem – determining the temperature of the sample (T) by the intensity of its thermal radiation (I) is approximated by function (2) and shown in Fig. 6,b:

$$T=39.01 \cdot ln(I-5781.91). \qquad (2)$$



a



b

Fig. 6. Intensity of the thermal radiation of the sample vs its temperature (a). Sample temperature vs intensity of its thermal radiation (b)

4. TEMPERATURE MONITORING OF THE IRRADIATION CHAMBER DURING EXPOSURE

The developed pyrometric technique was applied during an experiment on the irradiation of samples in a specially developed supercritical water convection loop (SWCP) with a scanning electron at the LU-10 electron accelerator [10]. The irradiation cell (IC) is a section of the loop, which includes four tubes-containers made of stainless steel with the samples placed in them. The IC was located close to the exit window of the accelerator. Fig. 7 shows the mirrored section of the loop during preparatory for the experiment.

In order to obtain a profile of the temperature distribution of the irradiation camera cell surface in steady mode, several frames with different exposures were taken (Fig. 8). The exposure was changed in such a way that the Illuminance at the measurement point did not go beyond the linear part of the camera sensor response (see Fig. 3).

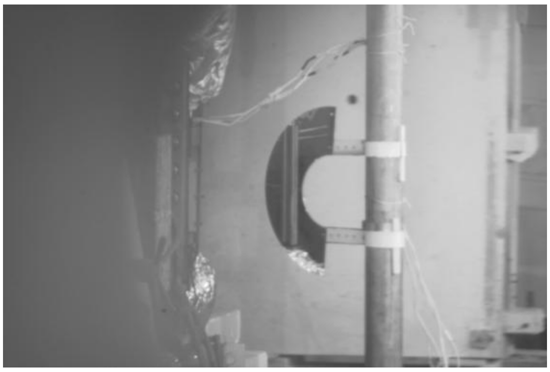
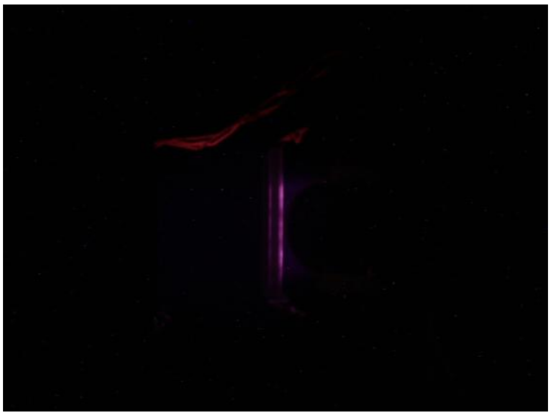


Fig. 7. The mirrored section of the loop with the irradiation cell



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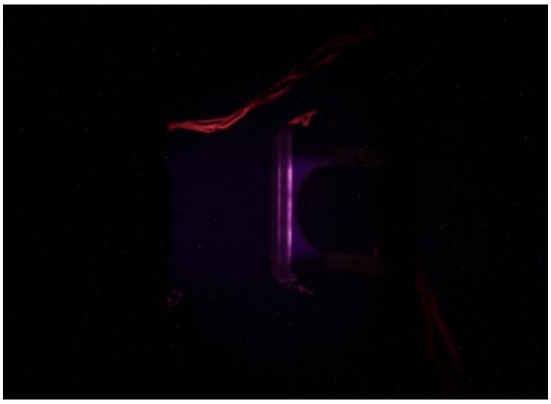

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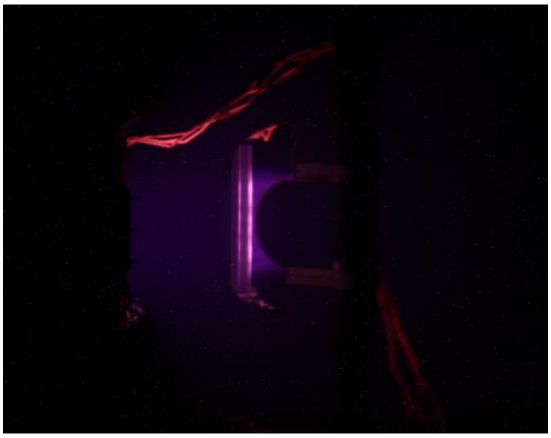

c

Fig. 8. Distribution of thermal radiation intensity made with different exposure, ISO units. (a – 400; b – 800; c – 1600)

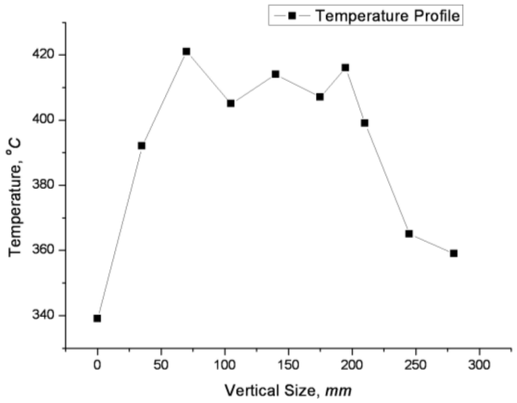

Fig. 9. Temperature distribution over the irradiation cell surface during exposure

The shooting was carried out in the complete darkness. The glow of the irradiation chamber was observed only after exceeding the temperature threshold of 330°C, which was confirmed by the readings of the temperature sensors. Thus, it is possible to assert the absence of a cathodoluminescent component in the recorded radiation.

The run of the supercritical water loop irradiation lasted more than 500 h at an average beam current of 0.76 mA and beam energy of 9 MeV. During the experiment, water pressure, its flow rate and temperature were monitored using 12 thermocouples placed in different points of the loop beyond irradiation zone.

In a steady regime, the temperature profile was determined on the surface of the loop section that was under the direct action of the scanned electron beam (Fig. 9). The zero mark corresponds to the lower edge of the irradiation cell. The obtained data are in good agreement with the readings of thermocouples and the results of calculations.

5. ANALYSIS OF UNCERTAINTY SOURCES OF THE MEASUREMENTS

The sources of uncertainty in a temperature measurement by pyrometric technique can be divided conditionally into several groups:

- uncertainty of calibration of the temperature measurement, a;
- exposure errors due to the instability of the mechanical shutter, b;
- uncertainty of digital image processing, c;
- uncertainty of approximation of the object’s temperature dependence on intensity of its optical radiation by function (2), d;
- errors in the photoelectric conversion channel.

The accuracy of the temperature measurement with a chromel-alumel thermocouple in the range 300…400°C declared by the manufacturer is ±16 μV (or ±0.5%), the accuracy of a digital thermometer is 1%.

Errors in the photoelectric converter are possible when the photographic exposure is incorrectly set. That may happen when the linear part of the response of the camera sensor is exceeded. Distortions are eliminated in the data transmission channel as the information is transferred in digital form.

To evaluate the instability of the exposure time of the camera’s mechanical shutter, a series of images of a stable light source with the same exposure was taken. Exposure deviation was ±3.2%. This component of the uncertainty can be reduced by using a digital camera with an electronic shutter.

Distortions in the optical path are possible due to inaccuracies in the adjustment of its elements. Optical geometric distortions of the lens can be neglected as it has focal length of 200 mm. That is much greater than the dimensions of the photo sensor (22.2×14.8 mm).

An error occurs when extracting the glow of an object by processing of its digital image due to the chosen number of pixels (up to 5%). It is possible to reduce this error by averaging the digital image over a multiplied number of pixels.

Thus, the total uncertainty of temperature measurements by this method can be defined as:

$$u=(a^2+b^2+c^2+d^2)^{1/2}. \quad (3)$$

Thus, the estimated uncertainty of temperature measurement by the proposed method is about 6.2% (k=1).

CONCLUSIONS

In NSC KIPT, a stand based on a high-current electron Linac has been created for testing the samples of the promising materials of a nuclear reactor cooled by water in a supercritical state. The stand includes a water convection loop with a cell for placement of samples of the test materials.

For continuous remote monitoring of the sample’s temperature, a measuring channel using the pyrometric method has been developed. The channel provides temperature measurements in the presence of a background of scattered gammas, and also of high-intensity electromagnetic radiation generated with the pulse systems of the accelerator. Those conditions were taken into account by creation of an optical path of the channel providing radiation protection of the converter of an optical-to-electrical signal, and also by development of software for processing of the latter. To register and process the optical signal, a remote-controlled DSLR camera was used, the working range of which was extended to the near-infrared range.

For channel calibration, a stand with the electrically heated samples of the materials from which the irradiation cell has been manufactured, was made. The stand performances provided its temperature calibration in the range corresponding to the actual operation mode.

The radiation tests of the channel for more than 500 h at a temperature of irradiation cell of 340…420°C confirmed its reliable operation.

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ДИСТАНЦІЙНИЙ КОНТРОЛЬ ТЕМПЕРАТУРНОГО РЕЖИМУ РАДІАЦІЙНИХ ВИПРОБУВАНЬ НА СИЛЬНОСТРУМОВОМУ ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ

С.К. Романовський, В.М. Борискін, Р.І. Помацалюк, В.Л. Уваров, Ю.О. Титаренко, В.Ю. Титов, В.А. Шевченко

У ННЦ ХФТІ розроблено методи та проводяться дослідження з оцінки радіаційної стійкості конструкційних матеріалів ядерних реакторів. У межах цих досліджень була розроблена надкритична водяна конвекційна петля з камерою опромінення випробуваних зразків пучком прискорювача електронів ЛУ-10 (енергія електронів 8…10 МеВ, потужність пучка до 10 кВт). Для дистанційного безперервного невпливового контролю температури поверхні опромінювальної камери у діапазоні 350…550°С розроблено пірометричну систему на базі цифрової дзеркальної фотокамери. У роботі викладено результати розробки системи, її калібрування та використання в умовах 500-годинного експерименту з опромінення зразків у водяній конвекційній петлі.