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Measurement of Temperature of Molten Zone at the Directional Crystallization of Blades of the Gas-Turbine Engine

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The review article is devoted to detailed analysis of known methods and ways for measuring the temperature parameters in the area of directional solidification of the melt of the rotor blades of gas-turbine engines. The analysis of existing methods of temperature control such as contactless methods and contact ones is made. As found, in further progress and development of devices and methods of temperature analysis, priority belongs to pyrometry. Relied on the advantages and disadvantages of existing methods, it is determined that the solution of this problem is possible with use of spectral and imaging pyrometry.

Оглядову статтю присвячено ґрунтовній аналізі відомих метод і способів міряння температурних параметрів у зоні розтопу за спрямованої кристалізації робочих лопаток роторів газотурбінних двигунів. Проведено аналізу наявних метод контролю температури як контактних, так і безконтактних. Встановлено, що у подальшому проґресі та розвитку приладів і способів аналізи температури пріоритет належить пірометрії. Спираючись на недоліки та переваги наявних метод, визначено, що розв'язання поставленої проблеми можливе з допомогою використання спектральної та телевізійної пірометрії.

Обзорная статья посвящена основательному анализу известных методов и способов измерения температурных параметров в зоне расплава при направленной кристаллизации рабочих лопаток роторов газотурбинных двигателей. Проведён анализ существующих методов контроля температуры как контактных, так и бесконтактных. Установлено, что в дальнейшем прогрессе и развитии приборов и способов анализа температуры приоритет принадлежит пирометрии. Опираясь на недостатки и преимущества существующих методов, определено, что решение поставленной проблемы возможно за счёт использования спектральной и телевизионной пирометрии.

Keywords: temperature measurements, molten zone, directional solidification, spectral pyrometry, imaging pyrometry, bispectrum pyrometry.

Ключові слова: вимірювання температури, зона розплаву, направлена кристалізація, спектральна пірометрія, телевізійна пірометрія, біспектральна пірометрія.

Ключевые слова: измерение температуры, зона расплава, направленная кристаллизация, спектральная пирометрия, телевизионная пирометрия, биспектральная пирометрия.

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1. INTRODUCTION

Almost every scientific research or manufacturing process requires measurement and measurement data, so there is no doubt that without the development of methods and tools for measuring the progress of science and technology is impossible.

Temperature measurements, in particular, are very important in terms of further progress of research and development of priority sectors of metallurgical industry, mechanical engineering (aerospace and automotive), and in tool building and electrical engineering. One of the most important processes in these areas is directional solidification method that is used for production of monocrystalline structure. For instance, the rotor blades of gas turbine engines (GTE).

Directional solidification (DS) is widely used for deep cleaning of various organic and inorganic substances from impurities [1]. The main goal of the DS process is a growing monocrystals of various substances. There are technological options based on DS that exercise directed heat removal from the border of phase transition that is in turn directed movement of crystallization front along the sample (see Fig. 1) [2]. This movement (usually with a constant speed) is carried out forcibly by gradually moving the heating and cooling zones [1].

High level of operational properties of materials manufactured by directional solidification are largely based on microstructure features formed during the directional solidification, homogeneity, high dispersion, and orientation along the direction of heat.

Currently, the directional solidification process is widely used for the rotor blades of gas turbine engines with directed and monocrystalline structure. The choice of process parameters to ensure the required quality of castings, castings depends on the geometry and design of the installed thermal units [3].

Turbine blades (Fig. 2) are among the most complex and important details of GTE. They operate at high temperatures and pres-

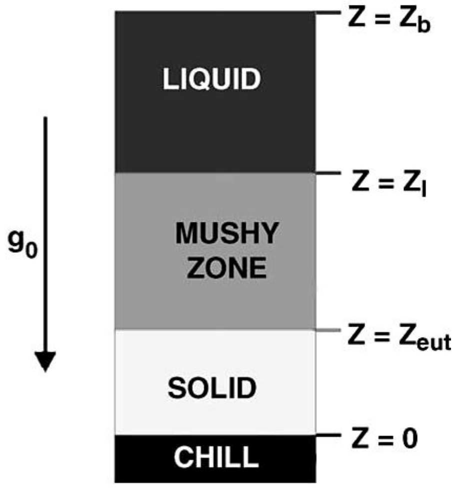

Fig. 1. Moving zones of phase transition [2].

sures. The reliability of turbine blades depends on resources and efficiency of turbine engine operation. Reliability of blades, in turn, is determined by the quality of their production, namely macro and microstructure, geometry of the casting and its thermal properties [4].

Given the growing competition in the global market of aviation instrumentation, which makes high demands to improve reliability,

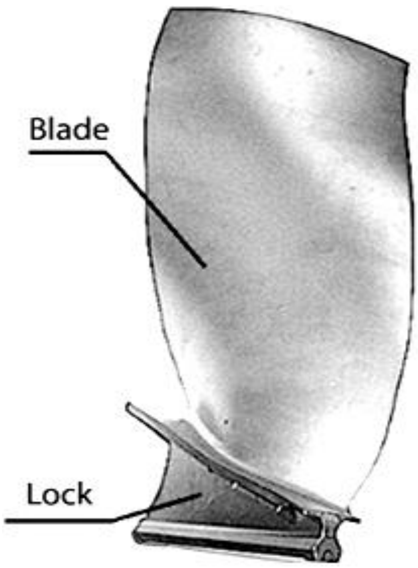

Fig. 2. Working gas-turbine engine (GTE) blade.

working capacity and efficiency of GTE, developers and producers are facing the task of increasing the guaranteed lifespan of GTE, increased engine power while reduced total mass.

It is known that the resource efficiency of engines defined by the turbines capabilities (installation with the rotational movement of the working body—rotor), and especially the most loaded part of it—blades. Stiffness of temperature and power conditions leads to the development of structures and the use of monocrystalline blades structure (compared to the blade, which has polycrystalline structure, the monocrystalline blade strength and heat resistance is 9 times higher, and resistances to oxidation and corrosion—3.5 times [5]). Therefore, there is a problem detailed study of the directional solidification of GTE blades, its automation and computerization, requiring the use of special measuring techniques (SMT) for measurement, control and management of major process parameters such as temperature field and the velocity of the crystallization front.

Therefore, the goal of this work consists in extended and thorough analysis of the known methods and ways to measure the temperature settings in melting zone at DS of rotor blades of GTE.

2. TEMPERATURE MEASUREMENT METHODS

There are two main classes of temperature measuring instruments: contact and contactless. [6]. The first one means thermometry based on contact with the object in which to determine the temperature, and the second one means widely known pyrometry—the process of measuring the surface temperature of hot bodies using the information contained in the radiation [7].

Contact measurement tools rely on direct contact of measurement tools with the object, resulting, in the ideal case, to thermodynamic equilibrium of transducer and the object. Currently, there are about a hundred thermometry methods, however only a small part of them are widely used. Effects of different devices for determining the temperature (thermometer) are based on the temperatures. Traditional means of measurement are liquid thermometers, thermocouples and others [8].

In contact thermometry, temperature is always measured by its own temperature, which, in under a number of conditions, accurately matches the temperature of the object being studied in contact. Contact thermometers are common in the temperature range from cryogenic to 1000–1500 K. In many cases, they do not provide the required performance in measurements, spatial resolution and speed of measurement; also, they are not suitable at high temperatures. In addition, this class of measurements possesses disadvantages as follows: the object is distorting temperature field while inserting the sensor; temperature transducer's temperature is always different from the true temperature of the object; the upper limit of temperature measurement is limited by the properties of the materials of which sensors are made [9].

In addition, a number of important problems associated with measuring the temperatures off the reach (zone melting, directional solidification) and moving objects (Metiz of aluminium, extrusion of profiles) cannot be settled by contact method. Also, contact temperature measurement is sometimes quite expensive. This applies in particular in the steel smelting process, where temperature of molten metal is usually determined by the thermocouple, which is expensive and after immersion in the molten metal thermocouples are no longer suitable for use, as their sensor immediately breaks down.

Thus, contact tools do not meet the set requirements for temperature measurement of molten zones of GTE blades during directional solidification.

The combination of these deficiencies thermometry necessitated the emergence in the late XIX and early XX century contactless temperature measurement. Around the same time, there are two basic methods for determining the non-contact temperature, namely radiation pyrometry, which is based on the Stefan–Boltzmann law [5] and spectral pyrometry, based on the Wien's value [5]. Later there was emerged another method of contactless temperature measurement, called TV pyrometry (TP) [10]. The TP method is based on the analysis of energy characteristics of monochromatic radiation. We know that today non-contact measurement methods have gained the biggest development and widespread adoption; this is considered in works [11–14]. These methods are based on registration of own thermal radiation of object. Object temperature is measured by the radiation characteristics described by Planck [15], which establishes a general link between the spectral density of radiation, wavelength and temperature radiator. Given the rapid development components (photodetectors, optics, microprocessors, etc.), pyrometry is gaining scale and importance.

Let us consider further the conduct and analysis of contactless pyrometry methods in the context of the task to control temperature parameters of the DS GTE blades.

2.1. Radiation Pyrometry

Radiation pyrometry method uses dependence of energetic brightness of radiation in a limited wavelength range on object's temperature. In other words, the brightness of radiation of an object depends on its temperature. Accordingly, by measuring the brightness of the radiation, we can measure (with some accuracy) the temperature of the object. Thus, the key element of radiation pyrometer is detector that converts radiant energy that passed through him to another physical quantity, often in current or voltage. Receiver is complemented with optical system that collects the radiation from the object in a defined angle. Electronic circuits and power systems convert and display the measurement result [16].

2.2. Spectral Pyrometry

The method of spectral pyrometry (SP) is based on the fact that, in the thermal radiation of optical spectra, there are many areas, which have similarities with Planck spectrum. It means that the studied objects are grey emitters in these spectral intervals. To find the interval and determine the temperature of the radiator, you have to register a wide range of continuous radiation [17].

In other words, the method of determining the temperature is based on the relative brightness measurements in a wide range of radiation of object that has its emissivity. The difference of the RP is not only in the usage of a large number of wavelengths (photosensitive line containing from 500 to 3600 pixels), but also compulsory testing of registered spectrum and blackbody spectrum.

2.3. Imaging Pyrometry

General method of using imaging measurement tools (IMT) is based on forming an image, converting it into digital code and using algorithms that provide the required accuracy of measurement of relevant parameters.

One of the most dynamic areas of modern pyrometry is pyrometry of radiation or imaging pyrometry, which is defined as a combination of high-temperature measurement methods, built on the dependence of the surface temperature of the body and the energy characteristics of its own radiation.

At present, the main driving force of scientific development of television measuring device (TMD) is television information and measuring system (TIMS), which is a combination of optical and electronic means by which information about the structure, properties and condition of object in its radiation is converted into an electrical signal. Figure 3 shows a physical model of the information signal in the imaging information and measuring system.

TIMS actually marked a new level of measurement technologies, and potentially they are most relevant to the requirements of modern geometric measurement, dynamic and amplitude parameters of many objects and processes [18].

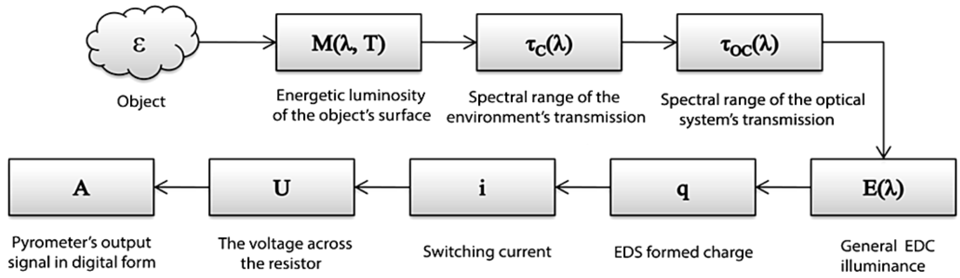

Fig. 3. Physical model of the information signal in television pyrometry (TP).

2.4. Physical Basis of Spectral Pyrometry

The SP is based [15] on the fact that the ratio of brightness of L blackbody radiation at two wavelengths λ uniquely identifies the temperature T (Fig. 4). The method consists in measuring and comparing the brightness of radiation at two wavelengths (λ_1 and λ_2). The number of unknowns is always greater than the number of measured values. To find the real temperature of the body, it is necessary that the number of measured values is equal to the number of unknowns.

The number of unknowns can be reduced if you know the ratio of two factors:

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{\varepsilon(\lambda_1)}{\varepsilon(\lambda_2)}, \tag{1}$$

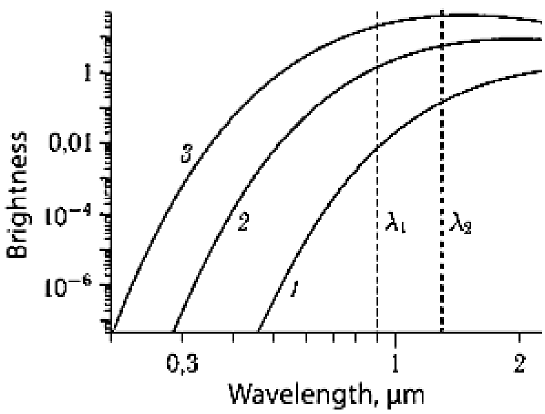

Fig. 4. The brightness of radiation for different temperatures of blackbody: 1000 K (*1*), 1500 K (*2*), and 2000 K (*3*). The ratio of the brightness L_1/L_2 at two wavelengths (λ_1 = 0.9 μm and λ_2 = 1.3 μm) decreases monotonically with increasing temperature.

where ε_1 and ε_2 are coefficients of emissivity of appropriate wavelengths λ_1 and λ_2 (in micrometres), respectively.

We can always relate unknown coefficients at these wavelengths. The introduction of additional conditions provides a system of two algebraic equations with two unknowns (T and ε) and real T. For example, there is the usual condition,

$$\varepsilon_1 = k\varepsilon_2 , \tag{2}$$

where k is a considered known value.

The relation between the spectral (T_c) and real (T) temperatures of the object during registration of radiation in Wien's areas is given by expression

$$T = \left[\frac{1}{T_c} + \frac{1}{C_2}\ln\left(\frac{\varepsilon_1}{\varepsilon_2}\right)\frac{\lambda_1\lambda_2}{\lambda_2 - \lambda_1}\right]^{-1} , \tag{3}$$

where $C_2 = 14.388$ μm.

The procedure of determining the temperature with spectral pyrometry method consists of brightness L_1 and L_2 measurement at two wavelengths, doing ratio correction L_1/L_2 using calculated or measured ratio $\varepsilon_1/\varepsilon_2$ and measuring temperature for the Planck's function with the same value $Z = (L_2\varepsilon_1)/(L_1\varepsilon_1)$, which determines the ratio of brightness blackbody radiation at these wavelengths.

Figure 5 shows the temperature dependence of the object's temperature on the value of Z on wavelengths $\lambda_1 = 530$ nm and $\lambda_1 = 650$ nm, if $C_2/(\lambda T) >> 1$ then

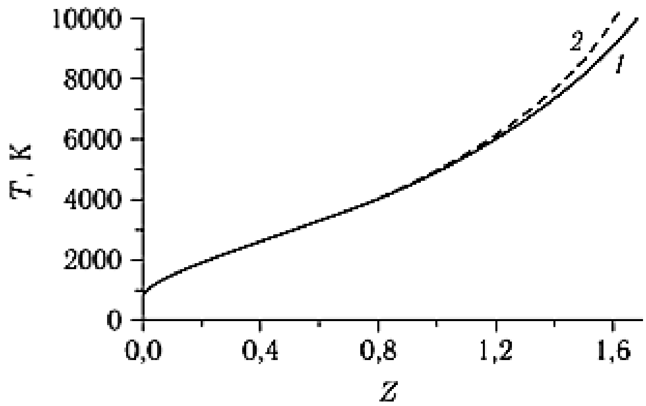

Fig. 5. Temperature dependence of the ratio of the actual brightness (with the emissivity of the two wavelengths) $Z = L_2\varepsilon_1/L_1\varepsilon_2$: *1*—Planck's model, *2*—Wien's model.

$$T = C_2 \frac{(\lambda_2 - \lambda_1)/\lambda_1\lambda_2}{\ln\left[Z(\lambda_2/\lambda_1)\right]} \tag{4}$$

At not very high temperatures, result obtained through Wien's approximation (curve *2*) coincides with the result of calculation using the exact Planck's formula (curve *1*).

When you use the exact formula of Planck, the desired spectral temperature can't be expressed explicitly, as in the Wien's formula, and calculating the temperature is performed by selection of the T value, substitution of which leads to best match the right (calculated) and left parts (measured experimentally):

$$\frac{L_2\varepsilon_1}{L_1\varepsilon_2} = \left(\frac{\lambda_1}{\lambda_2}\right)^5 \frac{\exp\left(C_2/\lambda_1 T\right) - 1}{\exp\left(C_2/\lambda_2 T\right) - 1}. \tag{5}$$

If the ratio $\varepsilon_1/\varepsilon_2$ is unknown, the desired spectral temperature can have significant difference from actual temperature.

2.5. Problems of Spectral Pyrometry

The problems of spectral pyrometry (SP) are considered in Ref. [10]. There are two main problems up to date. Those are relative expensiveness (compared with radiation pyrometer) and influence of the emissivity on the results of temperature measurement.

Pyrometer of spectral ratio (PSR) is structurally much more complicated than radiation one, and has a greater number of elements and it is harder to calibrate it. Availability of additional devices and nodes increases the amount of work of the manufacturer, so spectral ratio pyrometers are more expensive in comparison with radiation pyrometers.

Emissivity of measured objects affects the measurement results. Specifically, the PSR measurement result depends not only on the size of radiating ability or on changes from object to object, but more from the spectral dependence $\varepsilon = f(\lambda)$.

Figure 6 shows the spectral dependence of the emissivity of ε_λ for five types of metal: Fe, Ni, Cu, Ag, and Co [19]. They characterize most of metals and their alloys. From Figure 6, we can conclude that all dependences have roughly the same type of dependence: with increasing wavelength, spectral emissivity ε_λ decreases. This leads to the fact that long-wave signal receiver PSR appears low compared with shortwave one. That is why PSR results are often overestimated by 10%.

Calculating of the magnitude of error because of lowering of ε_λ is possible only if receiver bandwidth is very narrow and is not bigger

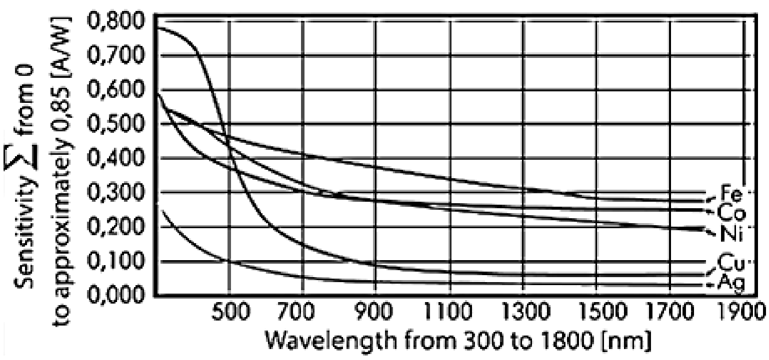

Fig. 6. Dependence of emissivity for Fe, Ni, Cu, Ag, and Co metals on the wavelength λ.

than 10–12 nm [9].

However, recently the majority of PSR uses two-layer photodiode structure, the upper layer of which has a maximum sensitivity in the short-wave spectrum, the bottom—in the long-wave. Strips of spectral sensitivity of the receivers make hundreds of nanometres, which eliminates the error due to instability of ε_λ. Also, information about ε_λ of most materials that need to be measured in the industry, is extremely limited or non-existent [19]. That is why the issue of correction of indications of PSR during measuring the temperature of objects with radiating ability, depending on the wavelength, had not been resolved. For a long time, users had to deal with this, as in many cases it is important not only precise knowledge of the measured temperature as following its repeatability in the process.

However, these problems are not critical and fundamental for solving this problem. So, the SP method can be used to measure temperature parameters in the melting area during directional crystallization (DC) of rotor blades of GTE, because the SP gives sufficient understanding of the thermodynamic temperature, and the measurement results do not depend on the coefficient of emissivity. Note that the result of the PSR measurement depends not only on emissivity values of its ability, but also changes from object to object, and also depends on the spectral dependence $\varepsilon = f(\lambda)$.

Another method one can use to solve the problem on measuring the temperature of the molten zone at the directional solidification of GTE blades is bispectrum pyrometry [20].

2.6. Physical Basis of Multispectral Pyrometry

The circuit in Fig. 3 suggests algorithm to create a mathematical model of formatting the information signal in multispectral pyrometry.

Power spectral luminosity of body at the temperature T [21],

$$M(\lambda, T) = \varepsilon \frac{C_1}{\lambda^5} \exp\left(-\frac{C_2}{\lambda T}\right), \tag{6}$$

then spectral illumination of matrix [12],

$$E(\lambda) = \frac{\pi}{4} \tau_C(\lambda) \tau_O(\lambda) \left(\frac{D}{f'}\right)^2 M(\lambda, T), \tag{7}$$

where D/f' is an aperture length, $\tau_C(\lambda)$ is a spectral transmittance environment, $\tau_O(\lambda)$ is a spectral transmittance of the optical system.

So, the signal at the output TP:

$$A(\lambda, T) = \varepsilon \frac{C_1}{\lambda^5} \frac{\pi}{4} \tau_C(\lambda) \tau_O(\lambda) \left(\frac{D}{f'}\right)^2 \exp\left(-\frac{C_2}{\lambda T}\right) K; \tag{8}$$

here, K is a conversion factor of charge-coupled device (CCD-matrix).

This model is correct for temperature measurement, if system parameters remain unchanged during the measurement.

The resulting signal is expressed in units of voltage, current or digital code will be used to analyse the surface temperature of an object of control using methods monospectral and multispectral pyrometry methods.

It is known that the multispectral pyrometry method is based on equality of the spectral luminosity relation of real body and absolute black body (ABB),

$$\frac{M(\lambda_1, T)}{M(\lambda_2, T)} = \frac{M_0(\lambda_1, T_c)}{M_0(\lambda_2, T_c)}; \tag{9}$$

$M(\lambda_1,T)$ and $M(\lambda_2,T)$—spectral luminosity body wavelengths λ_1 and λ_2, $M_0(\lambda_1,T_c)$ and $M_0(\lambda_2,T_c)$—spectral luminosity ABB wavelengths λ_1 and λ_2 with temperature T_c.

Further, les us determine the value of the surface temperature of an object of control using the following ratio:

$$\frac{\varepsilon(\lambda_1) M_0(\lambda_1, T)}{\varepsilon(\lambda_2) M_0(\lambda_2, T)} = \frac{M_0(\lambda_1, T_c)}{M_0(\lambda_2, T_c)}, \tag{10}$$

where $\varepsilon(\lambda_1)$, $\varepsilon(\lambda_2)$ are coefficients of emissivity of wavelengths λ_1, λ_2.

Combination of Planck's formula [21] and Eq. (10) results to

$$T^{-1} - T_c^{-1} = \ln\left(\varepsilon(\lambda_1)/\varepsilon(\lambda_2)\right) \Big/ \left(C_2(\lambda_1 - \lambda_2)/(\lambda_1 \lambda_2)\right). \tag{11}$$

Analysing the formula (11), we have that, for $\varepsilon(\lambda_1) = \varepsilon(\lambda_2)$, value T equals to value T_c, in other cases the true surface temperature of an object of control can be both higher or lower than temperature of spectral ratio. Indeed, if $\lambda_2 > \lambda_1$, then the sign of difference $T - T_c$ is determined by ratio between $\varepsilon(\lambda_1)$ and $\varepsilon(\lambda_2)$. If $\varepsilon(\lambda_1) > \varepsilon(\lambda_2)$, then $T < T_c$, and if $\varepsilon(\lambda_1) < \varepsilon(\lambda_2)$, $T > T_c$.

Using the concept of equivalent wavelength (EW), that is a symbol of a wavelength λ_{ex} of monochromatic radiation, under which the output device forms the same signal as under the real radiation, it allows us to rewrite formula (11) in a form

$$\frac{1}{T} - \frac{1}{T_c} = \frac{\ln\left(\frac{\varepsilon(\lambda_1)}{\varepsilon(\lambda_2)}\right)}{C_2}\lambda_{ex}, \tag{12}$$

where

$$\lambda_{ex} = \frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}. \tag{13}$$

Thus, as we see from dependence (12), multispectral pyrometry is also one of the methods that may solve the problem of measuring temperature parameters in the area of melting at the DC of rotor blades of GTE.

3. CONCLUSIONS

Reviewing and analysing the known methods and ways of measuring the temperature parameters in the area of melting at the DC of rotor blades of GTE, we found that further progress and development of instruments for analysing temperature pyrometry gets a higher priorities.

After analysing the main ways of pyrometry development, we highlighted a number of problems whose solution will bring many benefits in the use of non-contact measurement tools. One of the most important is elimination of the effect on the result of measurement of the spectral dependence $\varepsilon = f(\lambda)$ and other factors, that affect the accuracy of temperature measurement of PSR. As a solution to this problem, we suggested to calculate the optimal number of the wavelengths that should be measured.

We found that the task of measuring the temperature parameters in the area of melting at the DC of rotor blades of GTE could be solved by using as spectral ratio as a way of control. It should be noted that spectral pyrometry ratio is quite expensive, compared to the radiation one.

We also found that measuring the temperature parameters in the area of melting at the DC of rotor blades of GTE could be implemented with imaging pyrometry. At the same time, a significant number of issues of imaging pyrometry that are important in theoretical and practical aspects have not received adequate coverage. In particular, the scientific and technical literature has no systematic data about hardware of multispectral imaging pyrometry, reliably results of their use in scientific or technological practice.

We made a conclusion about the need for further study of spectral and imaging pyrometry as a means of measuring the temperature in the area of melting during directional solidification, as both methods can solve the problem.

REFERENCES

1. N. I. Gel'perin and G. A. Nosov, *Osnovy Tekhniki Kristallizatsii Rasplavov* [Fundamental Technique of Crystallization of Melts] (Moscow: 1986) (in Russian).
2. A. P. Boeira, I. L. Ferreira, and A. Garcia, *Mat. Sci. Eng. A*, **435–436**: 150 (2006).
3. V. P. Monastyrskiy, *Liteyshchik Rossii*, No. 7: 18 (2009) (in Russian).
4. B. N. Bazhenov, A. G. Chumakov, and S. I. Mel'nik, *Aviatsionno-Kosmicheskaya Tekhnika i Tekhnologiya*, No. 7 (43): 63 (2007) (in Ukrainian).
5. A. A. Inozemtsev and V. L. Sandrackiy, *Gazoturbinnyye Dvigateli* [Gas-Turbine Engines] (Moscow: 'Aviadvigatel': 2006) (in Russian).
6. A. M. Belen'kiy, M. Yu. Dubinskiy, M. G. Ladygichev, V. G. Lisienko, and Ya. M. Shchelokov, *Izmerenie Temperatury: Teoriya, Praktika, Ehksperiment: Spravochnoe Izdanie* [Measurements of Temperature: Manual Issue] (Moscow: Teplotehnik: 2007) (in Russian).
7. A. N. Gordov, *Osnovy Pirometrii* [Fundamentals of Pyrometry] (Moscow: Metallurgiya: 1971) (in Russian).
8. T. J. Quinn, *Temperature* (London: Academic: 1983).
9. M. A. Bramson, *Infrakrasnoe Izluchenie Nagretykh Tel* [Infrared Radiation of Heated Bodies] (Moscow: Nauka: 1964), vol. **1** (in Russian).
10. V. A. Porev, *Televiziyna Pirometriya* [Imaging Pyrometry] (Kyiv: AVERS: 2002) (in Ukrainian).
11. A. Frunze, *Fotonika*, No. 4: 32 (2009) (in Russian).
12. D. Ya. Svet, *Opticheskie Metody Izmereniya Istinnykh Temperatur* [Optical Methods of Measuring True Temperatures] (Moscow: Nauka: 1982) (in Russian).
13. Z. M. Zhang and G. Machin, *Experimental Methods in the Physical Sciences. Radiometric Temperature Measurements. I. Fundamentals* (Eds. Z. M. Zhang, B. K. Tsai, and G. Mashin) (Amsterdam: Elsevier: 2009), vol. **42**, pp. 1–28.
14. J. Hollandt, J. Hartmann, O. Struß, and R. Gärtner, *Experimental Methods in the Physical Sciences. Radiometric Temperature Measurements. II. Applications* (Eds. Z. M. Zhang, B. K. Tsai, and G. Mashin) (Amsterdam: Elsevier: 2010), vol. **43**, pp. 1–56.

15. A. N. Magunov, *Spektral'naya Pirometriya, Pribory i Tekhnika Ehksperimenta* [Spectral Pyrometry, Devices and Technique of Experiment], **4**: 5 (2009) (in Russian).
16. I. P. Brao, *Int. Research and Practical Conf. 'Innovations in Science' (October 29, 2014, Novosibirsk, Russia)* (in Russian).
17. A. N. Magunov, *Zhurnal Tekhnicheskoy Fiziki*, **80**, No. 7: 78 (2010) (in Russian).
18. M. O. Markin, O. M. Markina, and Yu. A. Agins'kyy, *Visnyk Natsionalnogo Tekhnichnogo Universitetu Ukrainy*, **46**: 64 (2013) (in Ukrainian).
19. A. E. Sheyndlina, *Izluchatel'nye Svoystva Tverdykh Materialov: Spravochnik* [Radiative Properties of Solid Materials: Manual] (Moscow: Energiya: 1974) (in Russian).
20. M. O. Markin, *East European Journal of Enterprise Technologies*, **1**, No. 5: 12 (2014) (in Ukrainian).
21. B. E. Paton and V. F. Lapchinskiy, *Svarka i Rodstvennye Tekhnologii v Kosmose* [Welding and Related Technologies in Cosmos] (Kiev: Naukova Dumka: 1998) (in Russian).