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THERMOPHYSICAL MEASUREMENTS

APPLICATION OF BELOW-CUTOFF WAVEGUIDES FOR PYROMETRIC MEASUREMENTS

A. V. Mamontov,[1] V. N. Nefedov,[2] and S. A. Khritkin[2]

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We consider the problems of measuring the temperature of objects heated in high-power microwave installations and show the advantages of using pyrometers for these purposes as compared with thermocouple temperature meters. The procedure of finding the characteristics of below-cutoff waveguides with circular cross sections intended for application in combination with pyrometric sensors is described. We also present the plots for the rapid evaluation of the geometric parameters of circular below-cutoff waveguides depending on the required inserted attenuation. An example of application of a circular below-cutoff waveguide in combination with a KM-1 pyrometer is presented.

Keywords: *below-cutoff waveguide, microwave installation, temperature measurements, pyrometer.*

The contemporary development of technological microwave equipment and its extensive application in various production processes is connected with the improvement of auxiliary equipment guaranteeing the required level of automation, monitoring, and safety of operation of microwave installations [1–4]. The application of the auxiliary equipment helps to check various parameters, such as mass, humidity, and temperature of the treated object [5–8]. The obtained information is used for the feedback in the process of control over the technological installation, e.g., to change the power of sources of the microwave energy and (or) the speed of motion of the conveyer belt with a treated material, which is necessary to obtain products of proper quality.

The temperature of the heated object is one of the most important technological parameters subjected to continuous monitoring in the course of heat treatment because it directly affects the quality of the obtained product. This parameter can be measured in microwave heating installations by two methods: by the contact method (with the help of thermocouple meters) and by the contactless method (by using pyrometers).

The thermocouple temperature meters are relatively inexpensive, reliable, and guarantee the required accuracy of measurements in a broad temperature range. They can be used to measure not only the surface temperature of the heated object but also the temperature at any point of its volume [9–11]. However, the use of thermocouple temperature meters in microwave heating installations has certain limitations, which substantially decrease the field of applicability of these meters. First of all, it is necessary to switch off all sources of microwave radiation, i.e., to interrupt the technological process for the period of measurements because it is necessary to exclude the presence of sensors in the electromagnetic field in view of possible manifestation of the antenna effect. This effect can de described as the formation of a parasitic electromotive force induced by the electromagnetic field at the ends of conductors of the thermocouple. This factor inevitably leads not only to substantial distortions of the indications of recording instruments but also to the formation of sparking between the conductors

[1] Research Institute of Advanced Materials and Technologies, Moscow, Russia; e-mail: niipmt@mail.ru.
[2] National Research University Higher School of Economics, Moscow, Russia; e-mail: 6034348@mail.ru.

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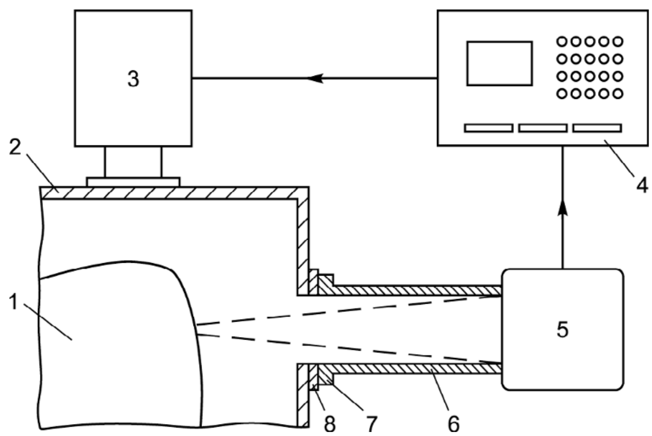

Fig. 1. Schematic diagram of connection of a pyrometer to the microwave heating chamber: *1*) heated object; *2*) microwave heating chamber; *3*) microwave energy sources; *4*) controller; *5*) pyrometric sensor; *6*) below-cutoff waveguide; *7*) flange; *8*) sealing gasket.

and, in the case of highly intense superhigh-frequency (SHF) electromagnetic fields, to the melting of the conductors caused by the Ohmic losses in them.

Pyrometric temperature meters are free of disadvantages typical of the thermocouples. This is why meters of this kind can be used to check the temperature of the heated object in the continuous mode without forced shutdowns of the sources of microwave energy. This enables the operator to control the process of heating with required accuracy: regulate the heating rate of the object and its thermostatting and change the speed of the transporter belt in the conveyor installation within the required limits. Nevertheless, pyrometers also have certain disadvantages. As the most important of these disadvantages, we can mention the dependence of the reliability of their indications on the emissivity of the heated object and the impossibility of measuring temperature inside the object.

The first disadvantage can be overcome by reprogramming the pyrometer according to the emissivity of the surface of heated object. Almost all contemporary devices (and even low-cost models) are equipped with this function. The influence of the second disadvantage is minimized by performing simple preliminary experiments with an aim to establish the dependence between the temperatures inside the object and on its surface. In most practical cases, the indicated dependence, as a rule, guarantees a sufficiently high accuracy satisfying the requirements of the technological process.

To measure the temperature of a heated object (e.g., in a beam SHF device) with the help of pyrometric sensors, it is customary to use below-cutoff waveguides of rectangular or circular cross sections. Circular waveguides are now especially widespread because they are less laborious in production. The below-cutoff waveguides realize the following two functions:

1) attenuate electromagnetic wave down to levels specified by the legislative regulations, thus providing the required level of safety of operation of the microwave installation [12, 13];

2) create the required field of vision for the pyrometer.

In Fig. 1, we present a schematic diagram of typical connection of the pyrometer in the control circuit of the microwave beam heating installation. The below-cutoff waveguide *6* with pyrometric sensor *5* is mounted on the wall of the microwave heating chamber *2* with the help of flange *7* equipped with sealing gasket *8*. The data from the sensor arrive at control unit *4* regulating the time of operation of the microwave energy sources *3*.

To compute the geometric parameters of a circular below-cutoff waveguide, it is necessary to find its length and inner diameter d depending on the required attenuation and the aperture of the pyrometric sensor. Moreover, in these calculations, it is necessary to take into account the length of the working wave λ and the possibility of propagation of E_{01}- and H_{11}-type waves in circular waveguides. The attenuation L introduced by a segment of the below-cutoff waveguide of length l is determined by the ratio of the amplitude of electric-field strength at the inlet of the waveguide E_{in} to its amplitude at the outlet E_{out} [14, 15]:

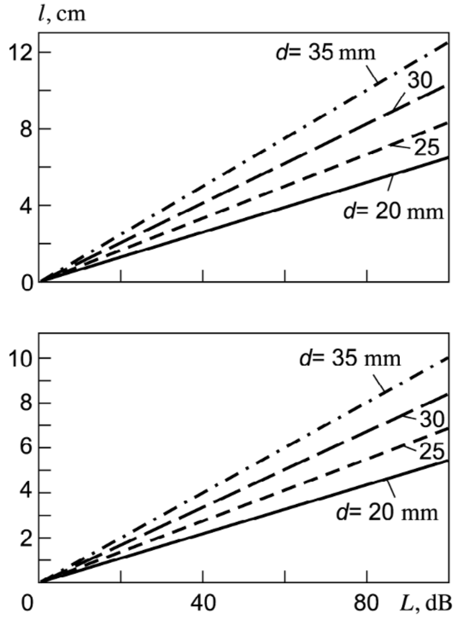

Fig. 2. Dependence of the length of a circular below-cutoff waveguide on the inserted attenuation for H_{11}-type (*a*) and E_{01}-type (*b*) waves and different diameters of the waveguide *d*.

$$L = 20\log\left(|E_{in}|/|E_{out}|\right) = 20\log e^{\alpha l} \cong 8.68\ \alpha l; \qquad \alpha = 2\pi/(\lambda_{cr}[1-(\lambda_{cr}/\lambda)^2]^{1/2}),$$

where α is the attenuation coefficient, and λ_{cr} is the critical wave length; for the wave E_{01}, we have $\lambda_{cr} \cong 2.62R$, whereas for the wave H_{11}, we get $\lambda_{cr} \cong 3.41R$; R is the radius of the below-cutoff waveguide.

The presented calculations are typical of H_{11}- and E_{01}-type waves with a frequency of electromagnetic oscillations of the microwave energy generators f = 2450 MHz and a wave length λ = 12.25 cm. The accumulated numerical data are presented in the form of plots, which enable us to determine the required parameters of the below-cutoff waveguide according to the given values of attenuation and the aperture of the pyrometer. In this case, the aperture of the pyrometer must be equal or smaller than the diameter of the waveguide.

In Figs. 2*a* and *b*, we present the dependences of the length of a circular below-cutoff waveguide on the inserted attenuation for H_{11}- and E_{01}-type waves and different diameters *d* of the waveguide. For practical applications, it is necessary to use the lengths of waveguides providing the required attenuation for both H_{11} and E_{01} waves.

To confirm these observations, we performed an experiment. For this purpose, we used a KM-1 pyrometer (Russia) with the following characteristics: the working temperature range –20–50°C, a temperature resolution of 1°C, the error of temperature measurement equal to ±(1.00 + 0.01%)ºC, a sighting index of 100:1, a setting time of 1 sec, the emissivity setting range 0.01–1.00, and an aperture of 32 mm. For this pyrometer, we produced a circular below-cutoff waveguide with a length of 130 mm and an inner diameter *d* = 35 mm. This waveguide guaranteed the attenuation of waves to a level of 100 dB. The tests performed in the beam chamber with a total power input of the microwave energy sources equal to 4.8 kW at a frequency of 2450 MHz confirmed the absence of any radiation different from the background radiation near the waveguide. The measurements were carried out with the help of a P3-33M analyzer (Russia) of the energy flow density of the electromagnetic fields.

The performed investigations enabled us to conclude that below-cutoff waveguides can be used in the technological microwave installations not only for measuring the temperature of heated objects but also for the organization of loading and unloading of heated materials (loose, liquid, and rod-shaped), ventilation holes, observation windows, lightening windows, etc.

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REFERENCES

1. V. N. Nefedov, A. V. Mamontov, V. P. Simonov, and V. V. Afanas'ev, "Hardening of the pipes of polymeric composite materials with the help of microwave radiation," *Elektron. Obrab. Mater.*, **53,** No. 4, 74–77 (2017).
2. V. N. Nefedov, A. V. Mamontov, V. P. Simonov, and V. V. Afanas'ev, "Measurement of the temperature of sheet materials in microwave travelling-wave structures," *Izmer. Tekhn.*, No. 10, 53–55 (2015).
3. V. N. Nefedov, A. V. Mamontov, and V. P. Simonov, "Measurement of the temperature of the walls of composite pipes during thermal processing in travelling-wave microwave systems," *Izmer. Tekhn.*, No. 8, 45–48 (2016).
4. S. Yu. Shakhbazov, V. N. Nefedov, E. V. Nikishin, et al., "Measurement of the distribution of the temperature field of materials in microwave resonators of complex shape," *Izmer. Tekhn.*, No. 6, 56–59 (2008).
5. A. V. Mamontov, V. N. Nefedov, A. L. Tuv, and D. A. Yazykov, "Investigation of the possibility of melting of basalt with the help of SHF energy," *Izmer. Tekhn.*, No. 9, 49–51 (2012).
6. Yu. S. Arkhangel'skii and E. M. Grishina, "Multifrequency SHF installations of dielectric heating," *Vopr. Elektrotekhnol.*, No. 2, 59–63 (2014).
7. A. V. Grigor'ev, T. A. Galiullin, and Yu. E. Sedel'nikov, "Measuring of the temperature of objects by radiometric methods," in: *Abstr. 9th Sci.-Eng. Crimean Microwave Conf. KryMiKo-99, SHF Engineering and Telecommunication Technologies*, Sevastopol (1999), Vol. 2, pp. 399–400.
8. G. A. Morozov and Yu. E. Sedel'nikov, *Low-Intensity Microwave Technologies (problems and realization)*, Radiotekhnika, Moscow (2003).
9. Yu. S. Arkhangel'skii, K. N. Ogurtsov, and E. M. Grishina, *Beam-Type Chambers of Superhigh-Frequency Electric Installations*, Poligrafiya Povolzh'ya, Saratov (2010).
10. V. A. Kolomeitsev, Yu. A. Kuz'min, D. N. Nikuiko, and A. E. Semenov, "Experimental investigations of the level of heating nonuniformity of dielectric materials and the absorbed power in SHF resonator-type devices," *Elektromagn. Volny Elektron. Sist.*, **18**, No. 12, 25–31 (2013).
11. A. A. Danilin, *Measurements in SHF Engineering*, Radiotekhnika, Moscow (2008).
12. GOST R 54372–2011, *Safety of Electrothermal Equipment. Part 6. Engineering Specifications for the Safety of Industrial Microwave Heating Equipment*.
13. Regulation 848–70, *Sanitary Code and Rules in the Operation of the Sources of High-, Ultrahigh-, and Superhigh-Frequency Electromagnetic Fields*.
14. Yu. V. Pimenov, V. I. Vol'man, and A. D. Muravtsov, *Technical Electrodynamics*, Radio i Svyaz, Moscow (2000).
15. I. V. Lebedev, *SHF Engineering and Instruments*, Vysshaya Shkola, Moscow (1970), Vol. 1.