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## THERMAL MEASUREMENTS

# TEMPERATURE DISTRIBUTION MEASUREMENT IN POLYMER COMPOSITE PIPES DURING THEIR HEAT TREATMENT WITH THE USE OF MICROWAVE RADIATION

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*A method is proposed for constructing radial type microwave devices forming a uniform temperature distribution throughout the volume of pipes made of polymer composite materials The results of theoretical and experimental investigations of the temperature distribution across the thickness of the pipe material are given. The advantages of microwave technologies for curing polymer composite materials compared to traditional methods are shown.*
***Keywords:*** *microwave device, microwave technology, electrodynamic system, microwave energy source, temperature distribution, composite material.*

Pipes made of polymer composite materials based on carbon, basalt, and glass fibers are presently widely used in various branches of industry. Such materials have high strength, low heat conductivity, high electrical insulation properties, small specific weight, resistance to chemical action, high level of operating loads, reliability, and longevity. The cost of assembly works of polymer composite materials is small. A thermosetting epoxy binder, which provides a high level of hydraulic resistance, is used during pipe production [1–3].

The traditional technologies of heat treatment of pipes made of polymer composite materials are based on convective radiation or contact heat transfer between the material being treated and the heat transfer agent. However, they have low heat conductivity, and the temperature gradients occurring in the material being treated make the technological heat treatment process long with considerable electricity consumption. This leads to nonuniformity of the structure of the material of the products, which is reflected on their physical and mechanical characteristics [4, 5].

One of the alternative methods of heat treating polymer composite materials is related to the use of microwave radiation as the thermal energy source [6–8]. The microwave method compared to traditional heat treatment methods has a number of advantages both from the viewpoint of reduction of electricity consumption, improvement of ecology, increase in the rate of technological processes of curing polymer binders, and increase of the uniformity of the structure, density, and strength of the products being obtained [9–11].

The main advantage of the proposed technological process of curing thermosetting binder is that the energy of microwave radiation instantaneously penetrates deep into the pipe material regardless of its thermal conductivity. Since the character of microwave heating is volumetric, the use of various designs of electrodynamic systems allows forming a uniform temperature distribution in the pipe material and avoiding temperature gradients taking place during traditional heating methods [12–14].

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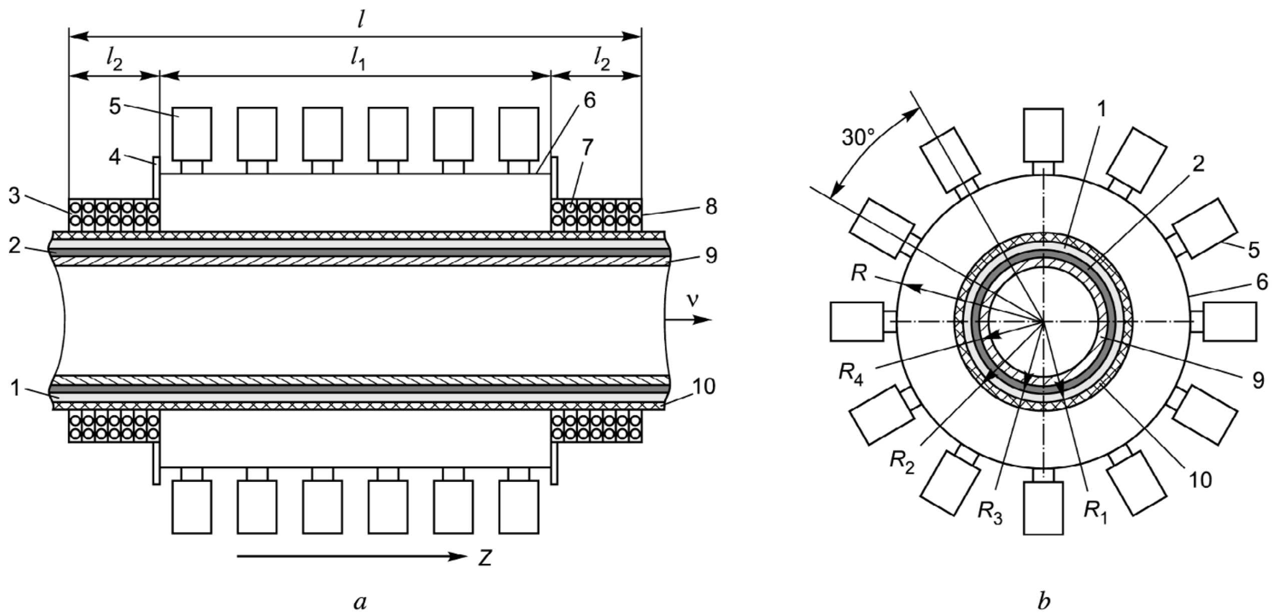


Fig. 1. Longitudinal section of continuous radial-type microwave device for curing polymer composite pipe (*a*) and transverse section of working section of this device (*b*): *1*) polymer composite pipe; *2*) inside pipe of heat-insulating material with small dielectric losses (for example, fluoroplastic); *3*) sluice chamber; *4)* connecting flanges; *5*) microwave energy source; *6*) cylindrical working chamber; *7*) water pipe of material with small dielectric losses (for example, polyvinyl chloride); *8*) contact plates; *9*) metal pipe; *10*) outside pipe of heat-insulating material with small dielectric losses (for example, fluoroplastic).

The use of microwave radiation in heat treatment of pipes made of polymer composite materials does not lead to heating of the surrounding air and metal components of equipment. The pipes being treated are located in heat-insulated holders with small dielectric losses during the time needed for heating and curing the polymer binder. Such a method allows reducing energy consumption in view of the absence of heat emission into the surrounding space. Moreover, the microwave method of heat treating pipes does not have inertia, which makes it possible to monitor and automate the technological process of curing polymer composite materials with the necessary accuracy [13, 14].

Scientific publications [15–17] give the results of the effect of microwave radiation on changes in the properties of thermosetting epoxy resins. It is shown that, compared to traditional technologies of curing polymer composite materials in various components of electric furnaces, microwave technology shortens curing time, reduces electricity consumption, decreases porosity, and increases the uniformity of the structure and strength characteristics of the material [18].

The present work presents the design of a radial-type microwave device for continuous production of pipes from polymer composite material based on basalt fibers. Such pipes have an outside diameter of 1000 mm and thickness of 30 mm. The proposed original device operates at a frequency of electromagnetic vibrations of 2450 MHz. The radial-type chamber consists of two cylindrical metal components. Microwave energy sources are arranged in a certain sequence on the outside surface, which provide a uniform temperature distribution on the outside surface of the polymer composite pipe material. The pipe material is located on the outer surface of the inside pipe between two fluoroplastic pipes in order to exclude heat emission into surrounding space, and the energy of the microwave radiation reflected from the inside metal pipe is absorbed anew by the pipe material. The length of the outside fluoroplastic pipe corresponds to the time needed for its curing. Addition of the incident and reflected power of the microwave radiation provides a uniform temperature distribution throughout the thickness of the pipe material.

Figure 1*a* shows a longitudinal section of the radial-type microwave device. The microwave device with length $l$ consists of a working chamber *6* having length $l_1$ and radius $R$. Microwave energy sources *5* for forming uniform heating of the pipe material *1* are arranged in a certain order on the chamber. The cylindrical working chamber *6* in which the polymer composite pipe is heated is located between two sluices *3*, each of which has length $l_2$. The design of the sluice chambers is protected by an RF patent [19].

The pipe formed from the polymer composite material moves with speed $v$ along the $Z$ axis of the microwave device. The given pipe is located between two pipes *2* and *10* made of heat-insulating material. Such pipes have small dielectric losses, which helps to disregard heat emission into the surrounding space and to maintain the prescribed temperature during the time needed for complete curing of the material. Pipe *2* has contact with metal tube *9*. The mass of polymer composite tube *1* in the working chamber is 532 kg. The microwave power needed for heating the polymer composite pipe from 20 to 200°C corresponds to 57.6 kW during the time of action of microwave radiation of 22 min at a pipe speed of 8 m/h.

Figure 1*b* shows a transverse section of the heating working chamber of the radial-type microwave device for curing a polymer composite pipe. There are 72 microwave energy sources arranged in a certain sequence on the working chamber for uniform heating of the polymer composite pipe. The maximum output power of each source is 0.8 kW. The microwave energy sources have a mass of 10 kg and overall dimensions of 400 × 200 × 200 mm. Output of the microwave energy from the sources is accomplished by a waveguide, the transverse cross section of which is 72 × 34 mm, on the main $H_{10}$ wave type. The aperture of the waveguide is used as a radiating antenna.

To form a uniform temperature distribution on the surface of the pipe located at a distance of 400 mm from the cylindrical surface of the working chamber, six transverse sections were selected, in each of which 12 microwave energy sources were arranged around the circumference at an angle of 30° relative to one another. The distance between adjacent rows of the microwave radiation sources along the axis of the working chamber was 500 mm. There was no deviation of the calculated values of the temperature from its nominal value on the outside surface of the examined pipe after passing through the microwave device.

Sluice chambers *3* are provided to prevent escape of microwave radiation from the operating microwave device and to provide safe working conditions for the staff. The sluice chambers *3* are connected to the working chamber by special flanges *4* to prevent microwave radiation into the surrounding space. Above the surface of pipe *10* in the sluice chamber is a water-filled pipe of a material with small dielectric losses (polyvinyl chloride) *7*. Between the water pipes *7* and the outside surface of the sluice chamber *3* made in the form of a metal cylinder are metal plates *8* arranged in a periodic sequence, which have electrical contact with the outside cylindrical surface of the sluice chamber. The microwave radiation, falling between these plates, is repeatedly reflected from them and absorbed by the circulating water in pipes *7*.

The microwave device operates in the following way. The polymer composite pipe having an outside radius $R_1$ is located on a pipe with radius $R_3$ made of a heat-insulating material (for example, fluoroplastic) with small dielectric losses. The pipe material moves through the microwave device at speed $v$ between two pipes in the form of fluoroplastic pipes. The pipe material passes through the slice chamber and enters the working heating chamber. A uniform temperature distribution throughout the volume of the pipe material being treated is formed in this chamber by means of the microwave radiation sources. Then the pipe passes through the sluice chamber absorbing the microwave radiation. Experimental investigations established that the level of secondary radiation from the microwave device did not exceed 10 μW/cm$^2$, which meets the adopted safety standards for the staff. The proposed design of the microwave device allows a substantial reduction of energy consumption on the technological process of curing a polymer composite pipe, increase of productivity, as well as realization of uniform heating of the pipe throughout the entire volume in accordance with the requirements imposed on the technological process.

The Huygens–Kirchhoff method is used when calculating the diagram of microwave radiation from the aperture of the rectangular waveguide of the microwave energy source [20]. The temperature distribution across the thickness of the material of the polymer composite pipe can be calculated by the formula

$$T(R) = T(0)e^{-2\alpha R},$$

where $T(R)$ is the temperature of the pipe material at distance $R$ from its outside surface; $T(0)$ = 200°C is the temperature on the outside surface of the pipe; and $\alpha$ is the attenuation constant of the amplitude of the electric field strength in the polymer composite material.

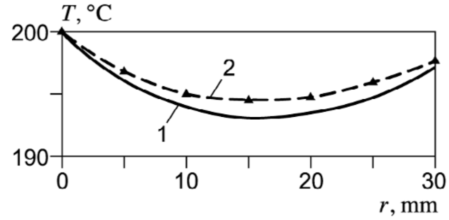


Fig. 2. Calculated (*1*) and experimental (*2*) dependences of temperature distribution over the pipe material thickness.

In the first approximation, the attenuation constant of the amplitude of the electric field strength is determined by the expression

$$\alpha = \pi\varepsilon'' / (\lambda\sqrt{\varepsilon'}),$$

where $\lambda$ is the wavelength of the microwave radiation source; $\varepsilon''$ is the imaginary part of relative permittivity of the pipe material; and $\varepsilon'$ is the real part of permittivity of the pipe material.

Figure 2 shows the calculated and experimental dependences of the temperature distribution through the thickness of the pipe material. Experimental investigations to measure the temperature of the polymer composite material of the pipe were carried out after disconnecting microwave radiation at the outlet from the microwave device. The temperature was measured over the thickness of the pipe material every 5 mm with consideration of reflection of microwave radiation from the metal pipe *9*. The temperature on the inside surface of the pipe material was 197°C, and on its outside surface 200°C. The difference between the calculated and measured characteristics of the temperature distribution did not exceed 3°C. With consideration of the reflected power from the inside surface of the metal pipe, the deviation of the temperature across the entire thickness of the pipe from the nominal value did not exceed 7°C.

*Main parameters of the microwave device and treated pipe material*

| | |
|---|---|
| Operating frequency of electromagnetic field vibrations | 2450 MHz |
| Output power of microwave energy source | 0.8 kW |
| Microwave power of device | 57.6 kW |
| Number of microwave energy sources | 72 |
| Total length of microwave device, $l$ | 6000 mm |
| Length of working heating chamber, $l_1$ | 3000 mm |
| Length of sluice chamber, $l_2$ | 1500 mm |
| Radius of working heating chamber, $R$ | 900 mm |
| Pipe radius: | |
| outside, $R_1$ | 500 mm |
| inside, $R_2$ | 470 mm |
| Speed of pipe material in microwave device, $v$ | 8 m/h |
| Temperature of pipe material: | |
| initial | 20°C |
| final | 200°C |
| Heat capacity of pipe material | 0.84 J/(g·°C) |
| Density of pipe material | 1.9 g/cm$^3$ |
| Relative permittivity of pipe material: | |
| imaginary part, $\varepsilon''$ | 0.13 |
| real part, $\varepsilon'$ | 4.5 |
| Thermal conductivity of pipe material | 0.46 W/(m·K) |

**Conclusion.** An equivalent model of a continuous radial-type microwave device for curing pipes made of polymer composite material is proposed and the main parameters of this device are given. The microwave device substantially reduces energy consumption on the technological process of curing a polymer composite pipe and increases productivity. The level of secondary radiation from the microwave device does not exceed 10 $\mu W/cm^3$, which meets the necessary safety standards of the operating staff and does not disturb the operation of nearby electronic equipment. The article's authors showed that the resultant temperature distribution across the surface and transverse section of the dielectric pipe in the proposed design of the radial-type microwave device satisfies the requirements of the technological process.

The innovation of the proposed method of calculating the temperature distribution is that the dependence of the dielectric parameters of the treated material on the change in temperature is taken into consideration.

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