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MEASUREMENTS OF THE TEMPERATURE OF THE WALLS OF COMPOSITE PIPES DURING THERMAL PROCESSING IN TRAVELLING-WAVE MICROWAVE SYSTEMS

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A design is proposed for microwave systems which produce a uniform temperature distribution over the transverse cross section of dielectric pipes. A method for calculating the temperature distribution over the thickness of pipes made of composite materials is examined.

Keywords: *microwave system, temperature distribution, dielectric material, waveguide, delay system, microwave power source.*

Pipes made of polymer composite materials are now widely used for water supply systems in roads, residences, and agriculture. These pipes have high chemical stability, low thermal conductivity, mechanical durability, and environmental acceptability, so that they can be used for drinking water lines. The traditional methods of hardening pipes involve heating them to a specified temperature by electrical heaters and maintaining the temperature for the time necessary to harden the material with the heat transfer into the surrounding medium taken into account.

A thermally hardened polymer binder with a low thermal conductivity is used in fabricating composite pipes based on glass or carbon fibers. Thus, a nonuniform temperature distribution is produced over the transverse cross section of a pipe when work pieces are heated by a thermal energy source. This leads to a gradient in the chemical reaction rate during hardening, internal stresses, and, therefore, to deterioration of the physical and mechanical properties of the product. In addition, prolonged exposure to high temperatures disturbs the homogeneity of the material and destroys the surface layers of dielectric pipes.

Microwave radiation makes it possible to heat the dielectric pipe uniformly and to eliminate internal thermal stresses in the course of the polymerization reaction which takes place uniformly over the entire volume; this leads to high durability of the work pieces [1–5]. A microwave system consisting of two sections is used for uniform heating of the pipes. In the first section, the heating element is in the form of a circular waveguide which creates a maximum temperature at the inner surface of a circular waveguide which falls off with radius toward the outer surface. The second section is a delay system in the form of an iris waveguide which creates a maximum temperature at the outer wall of the pipe which falls off gradually toward the inner wall. In this way, the combined temperature distribution from the two sections of the microwave system is uniform over the entire cross section of the pipe walls.

Each of the two sections of this device consists of an electrodynamic system. At one end this system is matched to the microwave source and at the other, to a water load in which a sensor detects the unused power in order to monitor the process. Figure 1 is a plan view of a two-section system for thermal processing of dielectric pipes with outer and inner diameters of 60 and 40 mm, respectively. The working frequency of the electromagnetic field is 2450 MHz. The microwave energy from the source *1* enters the first section of the system, which is in the form of a circular waveguide *2*, and is absorbed by a composite polymer pipe *3*. The pipe *3* is positioned between two teflon pipes and is moved along the axis of the waveguide. The unused

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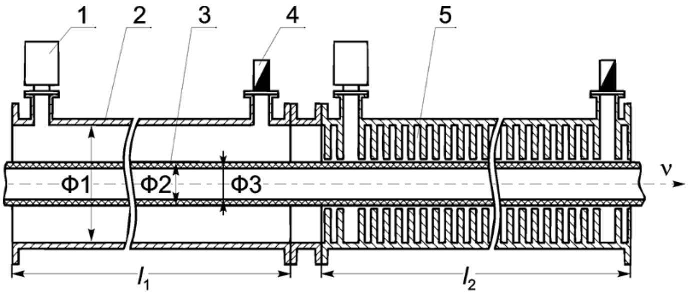

Fig. 1. Microwave system for thermal processing of dielectric pipes: *1*) microwave source; *2*) circular waveguide; *3*) dielectric pipe; *4*) matched load; *5*) iris waveguide; Φ1, diameter of circular waveguide; Φ2, outer diameter of dielectric pipe and iris waveguide; Φ3, inner diameter of dielectric pipe; l_1 and l_2, lengths of circular and iris waveguide sections, respectively; *v*, velocity at which dielectric pipe moves.

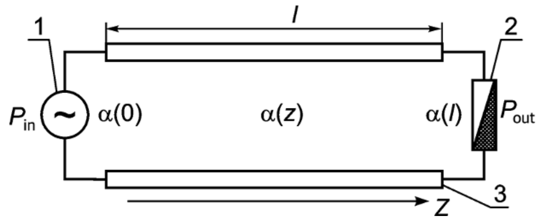

Fig. 2. Equivalent circuit of a section of the microwave system for thermal processing of dielectric pipes: *1*) microwave source; *2*) matched load; *3*) pipe of composite material that is uniform over its length; *l*, length of the electrodynamic system; *Z*, longitudinal coordinate axis; α(0) and α(*l*), damping constants for the amplitude of the electric field strength in the processed material at the beginning and end of the microwave system; α(*z*), running value of the damping constant for the amplitude of the electric field in the microwave system.

energy is absorbed by a water load *4*. Then the pipe enters the second section of the microwave system, which consists of an iris waveguide *5* in which microwave energy from the source is absorbed by the pipe and the unused energy, by a water load.

The sections of the microwave system are not coupled by an electromagnetic field, since they are decoupled by a supercritical circular waveguide mounted between them. The structures in which the electromagnetic energy propagates in the direction of motion of the material are referred to as longitudinal interaction devices. Each section of the system is matched to the microwave energy source and a water load. In this case, there is no reflected wave in the sections, but only a wave travelling from the source to the load. For example, in the first section of the microwave system an E_{01} wave propagates. The equivalent circuit for both sections of a longitudinal interaction system in the travelling wave mode with a loaded line is shown in Fig. 2 [6–9]. Microwave energy from the source *1* enters the heating element (the circular or iris waveguide) of length *l* with material in the form of a pipe *3* that is to be heated. The unused energy is absorbed by a load *2*.

We now consider the temperature distribution along a dielectric pipe in the steady state for the section of a microwave system with a circular waveguide heating element. The temperature distribution in the pipe material along the *Z* axis is given by [6]

$$T(z) - T_{\text{ini}} = P_{\text{in}} \exp(-2\alpha_{\text{ini}} z) 2\alpha_{\text{fin}} f^2(Z, T)\tau \Big/ [\pi(r_2^2 - r_3^2) c_{\text{d}} \rho_{\text{d}}], \tag{1}$$

where T_{ini} is the initial temperature of the dielectric pipe; P_{in} is the input microwave power; α_{ini} and α_{fin} are the damping constants for the electric field amplitude in the pipe material at the initial and final temperatures, respectively; $f(z, T)$ is a function that accounts for the temperature dependence of the dielectric parameters of the pipe material along the direction of

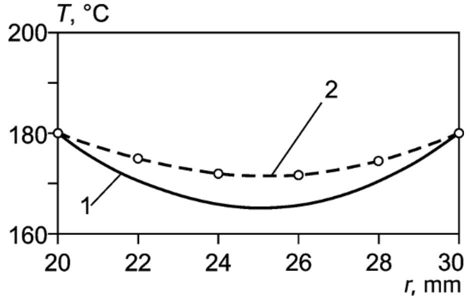

Fig. 3. Theoretical (*1*) and experimental (*2*) temperature distributions along the transverse cross section of a dielectric pipe in the steady state.

propagation of the electromagnetic field; τ is the time the material is in the microwave irradiation area; r_3 and r_2 are the inner and outer radii of the pipe, respectively; and c_d and ρ_d are the specific heat and density of the dielectric material.

The imaginary part of the relative dielectric constant for polymers has a linear temperature dependence over a wide range at the microwave frequency, 2450 MHz [6–9]. Here, $f(z, T)$ is given by

$$f(z, T) = \alpha_\mathrm{ini}/[\alpha_\mathrm{fin} - (\alpha_\mathrm{fin} - \alpha_\mathrm{ini})\exp(-2\alpha_\mathrm{ini}z)]. \tag{2}$$

The temperature in the circular waveguide is distributed nonuniformly over the transverse cross section of the pipe: it falls off from the inner to the outer diameter with the Bessel law dependence

$$T(r) = T(r_3)[J_1(2.405r/r_1)]^2, \tag{3}$$

where $T(r)$ is the radial dependence of the temperature of the pipe in the circular waveguide; $T(r_3)$ is the temperature at the inner surface of the pipe; $J_1(2.405r/r_1)$ is the first order Bessel function; and r_1 is the radius of the waveguide at the wave frequency of 2450 MHz for the fundamental E_{01} wave.

Since the critical wavelength in the waveguide for an E_{01} wave at this frequency is $\lambda_\mathrm{cr} = 2.62r_1$, we find $r_1 = 50$ mm.

In order to balance the temperature over the transverse cross section of the pipe in the microwave system, a second section was installed with a heating element in the form of an iris waveguide with an inner diameter of 60 mm corresponding to the outer diameter of the dielectric pipe. The iris waveguide produces a maximum temperature on the surface of the pipe which falls toward the inner diameter of the pipe with an exponential dependence. The iris waveguide is a delay system which concentrates the electric field at the surface by an amount that is determined by the delay coefficient k_d. As a first approximation, the temperature distribution in this system is given by

$$\left.\begin{aligned} T(r) &= T(r_2)\exp[-2kk_3r(1-\varepsilon'/k_\mathrm{del}^2)^{1/2}]; \\ T(r_3) &= T(r_2)\exp[-2kk_3r_3(1-\varepsilon'/k_\mathrm{del}^2)^{1/2}], \end{aligned}\right\} \tag{4}$$

where $T(r_2)$ and $T(r_3)$ are the temperatures at the outer and inner surfaces of the pipe, respectively; $k = 2\pi/\lambda$ is the vacuum wave number; $k_\mathrm{del} = \lambda/\lambda_\mathrm{del}$ is the delay coefficient with λ being the wavelength of the microwave source and λ_del, the retarded wavelength in the iris waveguide; $\varepsilon'_\mathrm{ini}$, $\varepsilon'_\mathrm{fin}$, $\varepsilon''_\mathrm{ini}$, $\varepsilon''_\mathrm{fin}$ are the real and imaginary parts of the relative dielectric constant of the material at the initial and final temperatures, respectively.

The lengths of the two sections were chosen so that the temperature at the outer and inner surfaces of the pipe after it has passed through the microwave system equaled the nominal value, i.e., $T(r_2) = T(r_3) = 180$°C. For this, it is necessary to solve Eqs. (1)–(4) by the method of successive approximations.

Figure 3 shows the theoretically calculated and experimental variations in the temperature over the transverse cross section of a pipe. In the calculated curve, the temperature at the outer and inner surfaces is 180°C, while the greatest deviation from this value occurs at the center of the pipe wall. In this region, the temperature is 166°C, a deviation of 14°C, or 7.7%. The deviation from the nominal temperature can be reduced by correcting the parameters of the microwave system, for example, by varying the output power of the microwave sources in each section or k_{del} in the iris waveguide.

Parameters of the microwave system and of the processed material

Working frequency of the electromagnetic field	2450 MHz
Output power of the microwave source for the first section	0.6 kW
Output power of the microwave source for the second section	0.6 kW
Standing wave ratio	
for the two sections within a bandwidth of 100 MHz, no more than	1.5
in the waveguide section at the working frequency	1.15
for the delay section system at the working frequency	1.25
Inner radius of waveguide r_1	50 mm
Outer radius of pipe r_2	30 mm
Inner radius of pipe r_3	20 mm
Length of waveguide section l_1	900 mm
Length of delay section l_2	300 mm
Velocity of pipe in the microwave system v	0.6 m/min
Delay coefficient k_{del}	3.0
Nominal temperature of pipe T_{fin}	180°C
Initial temperature of pipe T_{ini}	20°C
Loss factor	
$\varepsilon''_{\mathrm{ini}}$	0.12
$\varepsilon''_{\mathrm{fin}}$	0.18
Real part of the relative dielectric constant of the material	
at the initial temperature $\varepsilon'_{\mathrm{ini}}$	4.0
at the initial temperature $\varepsilon'_{\mathrm{fin}}$	4.5
Specific heat of material c_{d}	0.8 J/(g·°C)
Density of material ρ_{d}	2.4 g/cm^3

The experimental temperature distribution over the transverse cross section of the pipe (Fig. 3) shows that at the outer and inner surfaces the temperature is 180°C, while the maximum deviation from the nominal value also occurs in the central part of the pipe wall. There the temperature is 172°C, so that the deviation in temperature from the nominal value is 8°C, or 4.4%. The method of measuring the radial temperature distribution in the pipe is the following:

1) 4 3-mm-diam holes are made at distances of 22, 24, 26, and 28 mm from the axis of the pipe;

2) the time the microwave radiation acts on the transverse cross section of the pipe is chosen so that the temperature at the outer surface corresponds to that at the inner surface; and

3) the temperature is measured by a thermocouple after the microwave sources are turned off.

For personnel safety, special filters were installed on the inlet and outlet of the microwave system to prevent escape of microwave radiation from the working system. The design of these filters is patented [10]. They keep the level of spurious microwave radiation below the allowed limits. Measurements showed that the microwave leakage at a distance of 0.5 m from any point of the microwave system when it is operating did not exceed 10 μW/cm^2.

Conclusion. A design for travelling wave microwave systems with a uniform temperature distribution over the transverse cross section of dielectric pipes has been proposed. This microwave system consists of waveguide sections, which provide a peak temperature on the inner surface of the pipe, and sections with retarding systems which create a peak temperature on the outer surface. The superposition of the temperature distributions from the different sections of the microwave system yields a temperature distribution over the thickness of the pipe that is satisfactory for processing the pipe.

We have examined a model of a section of a microwave system in the form of a loaded long line and a method for calculating the temperature distribution over the thickness of pipes made of polymer composite materials under conditions such that the imaginary part of the relative dielectric constant has a linear dependence on the temperature variation. The discrepancy between the theoretically calculated and measured temperature distributions over the wall thickness of pipes made of polymer composite materials heated to 180°C did not exceed 6°C, while the variation in the experimental temperature distribution over the pipe thickness relative to the nominal value was 8°C.

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