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EFFICIENCY OF HEATING METHODS FOR POLYMER FIBERS WITH FORMATION OF ADHESION COMPOUNDS

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Efficiency of contact and contactless methods of heating of a fiber polymer material upon formation of adhesion compounds between its layers is analyzed. The advisability of contact heating in the preliminary stage and contactless heating in the final stage of formation of compounds is shown.

The traditional technology of fabrication of filtering, shock- and sound-absorbing materials, and other engineering items from fiber materials based on thermoplastic polymers includes thermotreating to form adhesion binding between fibers [1]. Estimation of the efficiency of various methods of heating of fibers is the key problem in developing industrial technologies of fabrication of fiber-porous items.

In the present work we compare contact and contactless methods of heating of fiber polymer material in the fabrication of cylindrical items from this material by the reeling method.

The nonwoven rolled polypropylene fiber material whose parameters are given below was used in the experiments.

Contactless heating of the material by IR radiation is realized by absorption of radiation, heat conduction, and convection. The contribution of absorption dominates for polymer materials; therefore, in the subsequent calculations only this mechanism was taken into account.

Results of the analysis of the spectral characteristics of the source of IR radiation and absorption of the polymer fiber material are presented in Fig. 1. The spectral radiation density e_λ of the filament of the halogen lamp corresponds to black-body radiation with $T = 1900$ K. The spectral absorption coefficient a_λ of the polypropylene-based fiber material was determined using an IR-spectrometer. It is obvious that the material absorbs about 35% of the radiation of the lamp within the range of wavelengths of 3–4 μm.

The radiation density $E_{\lambda_2-\lambda_1}$ within the spectral range $\lambda_2 - \lambda_1$ was calculated using the tabulated functions $Z_\lambda(X_\lambda) = E_{0-\lambda}/E_{0-\infty}$ of the dimensionless wavelength coordinates $X_\lambda = \lambda/\lambda_{\max}$ [2]:

$$E_{\lambda_2-\lambda_1} = \sigma T^4 \left[Z_\lambda (X_{\lambda_2}) - Z_\lambda (X_{\lambda_1})\right].$$

For the given lamp the radiation density calculated using this formula is $E_{3-4} = 7.38$ W/cm^2, and the effective radiation density corresponding to the area under curve 3 (Fig. 1) is $E_{\text{ef}} = 2.58$ W/cm^2.

The radiation density absorbed by the polymer material $E = E_{\text{ef}}\, r/(\pi h)$. The power absorbed by an irradiated portion of material with area S equals $P = ES$. The heat required for heating of the material from T_0 to T_{m} equals $Q = cm(T_{\text{m}} - T_0)$. The heating time of the material to temperature T_{m}:

$$\tau = Q/P = \frac{cm\,(T_{\text{m}} - T_0)\,\pi h}{E_{\text{ef}} r}.$$

Figure 2 presents calculated dependences of the temperature of the polypropylene fiber material ($m = 5 \cdot 10^{-3}$ kg, $c = 1.63$ kJ/(kg·K)) on the time of heating by the lamp ($r = 0.065$ cm) and on the distance to the lamp

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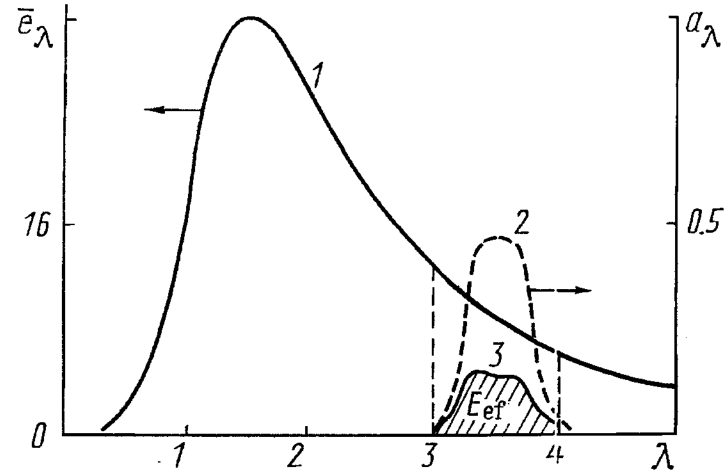

Fig. 1. Spectral density of radiation 1 of the filament of an IKG-220-1500 lamp, spectral absorption 2 of the polypropylene-based fiber material, and spectral effective radiation density 3. e_λ, W/(cm^2·μm); E_{ef}, W/cm^2; a_λ, arbitrary units.

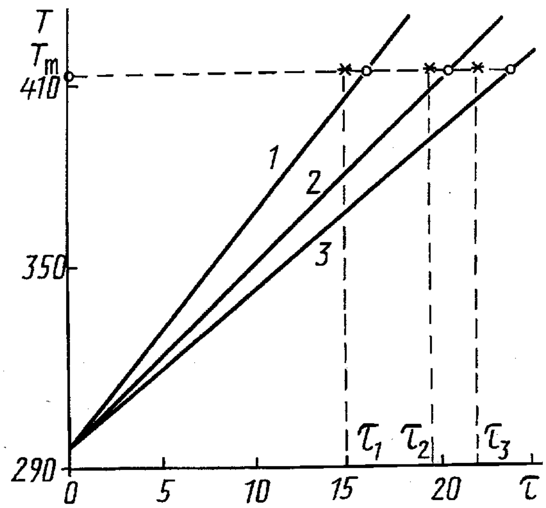

Fig. 2. Calculated dependence of the temperature T of the polypropylene-based fiber material on heating time τ and on distance to radiation source h = 1.00 cm (1), 1.25 cm (2), 1.50 cm (3). τ_1, τ_2, and τ_3, experimental values of the time of heating of the material to the temperature T_m. T, K; τ, sec.

as well as experimental values of temperature T_m. It is evident that holding of the material under the lamp for time $\tau < 1$ sec leads to elevation of its temperature by $\Delta T \simeq 5$ K. To heat the material to $T_m = 413$ K one should increase this time tenfold.

The contact method of heating consists in making a contact between the fiber material and the heating plate, which is kept at a constant temperature higher than that of the material. Under these conditions the temperature of the material is changed mainly along its thickness, whereas it is kept constant along the other dimensions.

The problem of the temperature distribution in an unbounded plate with thickness $R(0 < y < R)$ one surface of which ($y = 0$) possesses thermal insulation while the second one ($y = R$) is kept at temperature T_s is solved in [3]. Analysis of the solution has shown that the temperature within the plate levels off at T_s when the Fourier number $\mathrm{Fo} = \alpha\tau/R^2$, which has the meaning of generalized time, is $\mathrm{Fo} > 1.5$. For the polypropylene-based fiber material ($\alpha \simeq 10^{-7}$ m/sec, $R = 100\ \mu$m) Fo = 7 at $\tau = 0.7$ sec, i.e., the material manages to heat completely. The value $1.5 \ll \mathrm{Fo} = 7$ makes it possible to neglect the error arising from the nonidentical thermophysical characteristics of the air and of the ideal thermal insulation.

TABLE 1. Dependence of Density of Polypropylene Filtering Element (ρ) on Temperature of Heating Plate (T)

T, K	400	410	415	420	425
ρ, g/cm^3	0.39	0.38	0.40	0.53	0.93

The calculations are supported by the results of experiments which have shown that the polypropylene-based sheet fiber material is heated completely to the temperature of the heating plate (T = 400–425 K) in 0.3–0.5 sec. The important parameter of a fiber filtering material is its density, which characterizes not only the porosity of the filter but the amount of adhesion binding between fibers as well [4]. The density of a filtering element which is produced by reeling of the rolled polypropylene-based fiber material with the application of contact heating is increased with an increase in temperature (see Table 1). It is evident that exceeding the temperature 413–415 K leads to a substantial increase in density and, consequently, to structural changes of the material connected with melting and adhesion connection of fibers.

Thus, the most efficient method of adhesion joining of thermoplastic fiber materials is contact heating, which provides complete heating of the sheet along its thickness in a short time. Contactless heating elevates the temperature of the material insignificantly in the same time, and this method is advisable for the final stages of item formation when contact heating is difficult to realize and the temperature of fibers should be elevated by only a few degrees.

The results of investigations made it possible to determine temperature-temporal regimes of formation of filtering elements and to optimize the technological process and the design of equipment for fabrication of filters for fine treatment of liquids. This work has been carried out in the cooperation with the Korean Institute of Science and Technology within the framework of the Belarus-Korean Agreement.

NOTATION

e_λ, spectral density of radiation; T, temperature; a_λ, spectral absorption coefficient; $E_{\lambda_2-\lambda}$, $E_{0-\lambda}$, radiation density within the spectral region $\lambda_2 - \lambda_1$, and $0-\lambda$, respectively; λ, wavelength; $\lambda_{\max}$, wavelength of the maximum of black-body radiation; $E_{0-\infty}$, total density of black-body radiation; σ, the Boltzmann constant; E_{ef}, effective radiation density; E, radiation density absorbed by the material; X_λ, dimensionless coordinate; r, radius of the filament of the lamp; h, distance from the lamp to the surface of the material; S, area; P, power absorbed by the portion of the material; T_{m}, temperature of the onset of variations in the appearance, shrinking, and melting of the material; Q, heat; T_0, initial temperature of heating; c, specific heat capacity of the polymer; m, mass of the material being heated; τ, time of heating to T_{m}; y, coordinate; R, thickness; T_{s}, stabilized temperature; Fo, Fourier number; α, thermal conductivity of the material.

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