DETERMINATION OF THE THERMAL DIFFUSIVITY AND THERMAL
CONDUCTIVITY OF LAYERS OF POLYPROPYLENE AND POLYAMIDE
FIBERS

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Improved consumer and special properties can be conferred on synthetic fibrous materials
by radiochemical or chemical grafting of certain monomeric compounds onto their surface from
the gas phase [1, p. 109]. As a rule, the grafting process is accompanied by a considerable
heat evolution and can lead to heating of the fiber mass. Removal of the heat evolved in
the reaction is one of the important factors which determine the technological process param-
eters. To solve the problem of heat removal, it is necessary to know the thermophysical
properties of the specific polymeric fibrous materials under the conditions at which the
modification process is being carried out.

The object of the studies described in the present article was to determine the thermo-
physical characteristics of layers of the most widely distributed types of staple fibers —
polypropylene and Kapron (polyamide) — under various external conditions.

To determine the thermal diffusivity coefficients of the materials, we used the method
of recording the time distribution of temperature over the reactor section during processes
of nonstationary thermal conductivity [2, p. 128]. For this purpose we used the pilot setup
whose scheme is shown in Fig. 1. The assembly consists of a steel cylindrical reactor 115
mm in diameter and 340 mm tall having thermostatable walls (in which the process of fiber
modification is effected by gas-phase grafting), a vacuum-pumping system and pressure regu-
lation, and a thermostating system. The temperature in the layer of fibers was measured by
use of a system of thermocouples, located at various points in the reactor, which permitted
one to follow temperature changes in the material and temperature distribution over the cross-
section of the apparatus during warmup of the material.

The method of treating the experimental data which was used made it possible to deter-
nine the coefficients of thermal diffusivity and thermal conductivity with accuracies of 5%
and 10%, respectively.

The fiber-filled assembly is a system containing a porous material whose thermal con-
ductivity is a complex function of the nature of the material, the porosity of the pressure
system and the nature of the gas, the temperature, and other factors. It is difficult to
make full allowance for these factors in solving the corresponding equations. A number of
empirical relationships are given in the literature [2, p. 344] which permit one to determine
the thermal conductivity coefficients of porous materials, \( \lambda \); however, these relationships
contain serious assumptions and only afford the opportunity of ascertaining the order of mag-
nitude, or in the best case, the region in which the values of \( \lambda \) lie for specific systems.

For experimental determination of the value of \( \lambda_{\text{eff}} \), we investigated heat-transfer pro-
cesses from the outer surface of a cylinder into the volume of the material for the case of
a one-dimensional, nonstationary temperature field in accordance with the equation

\[
\frac{c_p}{\rho} \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)
\]

(1)

where \( c_p \), \( \rho \), and \( T \) are the heat capacity, density, and temperature of the fiber mass; \( t \) is
time from the start of warmup of the reactor walls; \( r \) is the distance from the reactor axis,
and the boundary conditions are

\[
T(r, 0) = T_0; \ T(R, t) = T_v
\]

(2)
The reactor wall was heated from the initial temperature, \( T_0 \), to the assigned temperature, \( T_f \), at which the process of wall heating with time is well described by the equation

\[
T_w = T_0 + (T_f - T_0) \left[ 1 - \frac{1}{\alpha} \left( e^{-\alpha t} + e^{-\beta t} \right) \right]
\]

(3)

with constants \( \alpha \) and \( \beta \), which, for the present reactor, are \( 1.33 \times 10^{-2} \) and \( 2.17 \times 10^{-3} \) sec\(^{-1} \), respectively.

The system of equations (1)-(3) describes the process of warming of a fibrous material in a cylinder with time. By solving these equations by the method of Laplace [2, p. 106], we obtained the dependence of the temperature inside a layer of fiber at any point of the reactor on the duration of reaction in analytical form. In particular, for points which lie on the cylinder axis,

\[
\theta(0, t) = \frac{1}{2} \left[ \frac{e^{-\alpha t}}{J_0 \sqrt{\alpha R^2}} \right] + \frac{e^{-\beta t}}{J_0 \sqrt{\beta R^2}} - \sum_{n=1}^{\infty} 2 \frac{\mu_n^2}{\beta R^2} \left( \frac{1}{\alpha^2} + \frac{1}{\beta^2} \right) \left( 1 - \frac{\mu_n^2}{\alpha R^2} \right) \left( 1 - \frac{\mu_n^2}{\beta R^2} \right) \frac{e^{-\mu_n^2 R^2}}{J_1 \mu_n}
\]

(4)

where \( \theta(r, t) = [T(r, t) - T_0] / (T_f - T_0) \) is the relative temperature of the material; \( J_0 \) and \( J_1 \) are the zero- and first-order Bessel functions of the first kind; \( \mu_n \) are the characteristic roots of the zero-order Bessel function of the first kind; and \( \alpha = \lambda_{\text{eff}} / \rho c_p \) is the coefficient of thermal diffusivity in the system.

Using a minicomputer, we performed a calculation of the temperature change on the reactor with time for various thermal diffusivity coefficients by relationship (4). The results of calculations are given in Fig. 2.

To estimate the thermal diffusivity coefficient under real conditions, we constructed a dependence of the calculated characteristic warmup time of the system (the time to reach \( \theta = 1/2 \)) on the thermal conductivity coefficient \( \tau_{1/2} = f(\alpha) \). By varying the value of the thermal diffusivity coefficient which was obtained for the warmup time of a real system, we obtained the best approach of the calculated dependence to the experimental results.

Values found for the effective coefficients of thermal diffusivity and thermal conductivity in a layer of polypropylene or polyamide fiber under various conditions are given below:

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Density of fiber layer, kg/m(^3)</th>
<th>Air pressure, Pa</th>
<th>Temperature range, deg C</th>
<th>( \sigma \cdot 10^7 ), m(^2)/sec</th>
<th>( \lambda \cdot 10^2 ), W/(m·deg)</th>
<th>( K_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>46</td>
<td>13.3</td>
<td>18–31</td>
<td>4.6</td>
<td>4.06</td>
<td></td>
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<tr>
<td></td>
<td>46</td>
<td>13.3</td>
<td>31–50</td>
<td>4.6</td>
<td>4.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>13.3</td>
<td>50–78</td>
<td>4.7</td>
<td>4.56</td>
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<td>13.3</td>
<td>78–95</td>
<td>4.8</td>
<td>5.27</td>
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<td></td>
<td>46</td>
<td>3.3 \times 10^{4}</td>
<td>18–51</td>
<td>5.2</td>
<td>4.56</td>
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<tr>
<td></td>
<td>46</td>
<td>1.3 \times 10^{4}</td>
<td>18–51</td>
<td>5.2</td>
<td>4.56</td>
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<tr>
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<td>46</td>
<td>10^{4}</td>
<td>18–51</td>
<td>5.4</td>
<td>4.73</td>
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</tr>
<tr>
<td>Polyamide</td>
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<td>18–62</td>
<td>4.2</td>
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<td>71</td>
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<td></td>
<td>71</td>
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<td>6.15</td>
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