

PROBLEM OF CHOOSING THE OPTIMUM REGIME FOR THE
TECHNOLOGICAL PROCESS OF VACUUM-FORCED IMPREGNATION

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The time expended on the process of vacuum-forced impregnation of porous layer with a viscoplastic liquid is calculated. The optimum regime for which this time is minimum is indicated.

High-strength and moisture-resistant insulation of monoliths is used in electrical mining equipment, operating under conditions of high humidity [1]. In order to obtain it, porous paper or glass micaceous insulation is first subjected to evacuation, under which the pressure of air in pores decreases to some value P_0 , after which in a vacuum chamber (autoclave) under a pressure P_f an epoxy compound is applied (the composition is based on the epoxy resin ED-22 and isomethyltetrahydrophthalic anhydride). The impregnated insulation is heated to the polymerization temperature of the compound ($T_p \sim 100^\circ\text{C}$), as a result of which the monolith forms. Since the compound enters the insulation from all sides, the air remaining in its pores is compressed, its pressure increases, and begins to retard further impregnation. At the same time, as this pressure increases the amount of air dissolved in the compound also increases, which permits carrying out complete impregnation of the insulation with incomplete preliminary evacuation. In order to increase the efficiency of the equipment used, it is necessary to shorten the time expended on the technological process of vacuum-forced impregnation indicated above as much as possible. For this purpose, the compound is heated (to a temperature $T_f < T_p$), since in this case its viscosity and initial pressure gradient decrease, while the percolation rate increases. On the other hand, the decrease in the evacuation time is related to the increase in P_0 and corresponding retardation of impregnation. Thus, in order to choose the optimum regime, it is necessary to determine the impregnation time as a function of the parameters of the process and of the residual pressure P_0 with which the total evacuation and impregnation time are minimum.

The epoxy compound has viscoplastic properties and its percolation can be described by the generalized Darcy law [2, 3]:

$$\mathbf{v} = \begin{cases} -\frac{k}{\mu}(\nabla P + j\mathbf{v}) & \text{for } |\nabla P| \geq j, \\ 0 & \text{for } |\nabla P| < j. \end{cases} \quad (1)$$

The unit vector \mathbf{v} is oriented opposite to the pressure gradient. The viscosity and initial pressure gradient are decreasing functions of temperature:

$$\mu = \mu_f \varphi(\theta), \quad j = j_f \psi(\theta), \quad \theta = \frac{T - T_0}{T_f - T_0}. \quad (2)$$

Adding to (1) the continuity equation for an incompressible fluid and the stationary heat-conduction equation

$$\text{div } \mathbf{v} = 0, \quad \text{div } \kappa \nabla \theta = 0, \quad \kappa = \kappa_f \varphi(\theta), \quad (3)$$

we obtain the complete system of equations for the problem being examined. Here it is assumed that the thermal conductivity of the impregnated insulation practically coincides with the thermal conductivity of the compound and, for this reason, its temperature dependence is the same as that of the viscosity [4].

On the boundary of the porous medium and the compound, the following conditions are satisfied:

$$P = P_f, \quad \theta = 1. \quad (4)$$

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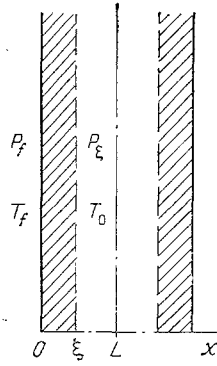


Fig. 1. Diagram illustrating the formulation of the problem.

On the moving percolation front, the air pressure in the pores equals the sum of the fluid and capillary pressures, while the temperature satisfies the heat transfer condition:

$$P = P_{\xi} - P_c, \quad \varphi \frac{\partial \theta}{\partial n} + h\theta = 0, \quad (5)$$

where \mathbf{n} is the normal to the surface of the front. In order to determine P_{ξ} , we shall use the Clapeyron equation

$$P_{\xi} = \frac{m_{\xi}}{\mu_m} \frac{RT_0}{V_{\xi}}. \quad (6)$$

We shall assume that the air compression process is isothermal. According to Henri's law, the mass of the gas, dissolved per unit volume of liquid, is proportional to the excess pressure. Thus [5],

$$m_{\xi} = m_0 - cV_0(P_{\xi} - P_0), \quad (7)$$

where c is a constant. At the time that impregnation ceases, all of the air must be dissolved in the compound. In this case, its pressure, according to (7), will equal

$$P_L = (1 + \lambda)P_0, \quad \lambda = \frac{\mu_m}{cRT_0}. \quad (8)$$

Taking into account (6)-(8), we obtain

$$P_{\xi} = P_L \left(1 + \lambda \frac{V_{\xi}}{V_0}\right)^{-1}. \quad (9)$$

Let us examine the case of impregnation of a two-dimensional infinite layer with thickness $2L$ (see Fig. 1). In this case, the solution of Eqs. (1) and (3), satisfying the boundary conditions (4) and (5), has the form

$$v = \frac{k}{\mu_f F(\theta_{\xi})} \left[\frac{1}{\xi} (P_f + P_c - P_{\xi}) \Phi(\theta_{\xi}) - j_f \Gamma(\theta_{\xi}) \right], \quad (10)$$

$$\Phi(\theta) = \frac{x}{\xi} \Phi(\theta_{\xi}).$$

Here

$$\Phi(\theta) = \int_{\theta}^1 \varphi d\theta, \quad F(\theta) = \int_{\theta}^1 \varphi^2 d\theta, \quad (11)$$

$$\Gamma(\theta) = \int_{\theta}^1 \varphi \psi d\theta, \quad P_{\xi} = P_0 \left(1 - \frac{\lambda}{1 + \lambda} \frac{\xi}{L}\right)^{-1}$$

The value of θ on the percolation front with $x = \xi(t)$ is determined, according to (5) and (11), by the equality

$$\Phi(\theta_{\xi}) = h\xi\theta_{\xi}. \quad (12)$$

Substituting into (10) $v = d\xi/dt$, we find the time for complete impregnation of the layer in

the form of a quadrature

$$t = \frac{\mu_f}{k} \int_0^L \frac{\xi F(\theta_\xi) d\xi}{(P_f + P_c - P_\xi) \Phi(\theta_\xi) - j_f \xi \Gamma(\theta_\xi)}. \quad (13)$$

For further calculations, it is necessary to give the functions Φ and ψ . The viscosity of the liquids decreases exponentially depending on the inverse absolute temperature [6]

$$\mu = A \exp(B/T),$$

where A and B are constants that characterize the properties of the liquid. Since in our problem, the relative change in the absolute temperature is small, this dependence is replaced by a linear dependence. Thus,

$$\varphi = \mu^* - (\mu^* - 1)\theta, \quad \mu^* = \frac{\mu_0}{\mu_f}. \quad (14)$$

We shall give the function ψ in a similar manner:

$$\psi = j^* - (j^* - 1)\theta, \quad j^* = \frac{j_0}{j_f}. \quad (15)$$

The indices 0 and f label quantities corresponding to the temperatures T_0 and T_f . From (11) and (12), we find

$$\begin{aligned} \Phi(\theta) &= \frac{1}{2} (1 - \theta) [\mu^* + 1 - (\mu^* - 1)\theta], \\ F(\theta) &= \frac{1}{3} (1 - \theta) [\mu^{*2} + \mu^* + 1 - (\mu^* - 1)(2\mu^* + 1)\theta + (\mu^* - 1)^2\theta^2], \\ \Gamma(\theta) &= \frac{1}{6} (1 - \theta) [2\mu^*j^* + \mu^* + j^* + 2 - (4\mu^*j^* - \mu^* - j^* - 2)\theta + 2(\mu^* - 1)(j^* - 1)\theta^2], \end{aligned} \quad (16)$$

$$\theta_\xi = \frac{1}{\mu^* - 1} (\mu^* + h\xi - \sqrt{1 + 2\mu^*h\xi + h^2\xi^2}).$$

Equations (13)-(16) for fixed values of the parameters of the process P_f and $T_{0,f}$ determine the impregnation time as a function of the residual air pressure in the pores. The latter practically coincides with the air pressure in the vacuum chamber [7] and for this reason its variation with time under evacuation $\tau = \tau(P_0)$ is easily determined experimentally. Thus, we obtain the time expended on the entire process of vacuum-forced impregnation as a function of P_0 .

$$t + \tau = f(P_0). \quad (17)$$

From the condition that the function f is minimum, we find the shortest time for the process examined and the corresponding optimum value of P_0 . For arbitrary values of the heat-transfer coefficient h , this problem can be solved only numerically. An analytic expression for t is obtained in the limiting cases $h = 0$ and $h = \infty$. The first case corresponds to impregnation by a liquid with constant temperature $T = T_f$ and the second occurs with the boundary condition $T_\xi = T_0$.

The corresponding values of t have the form

$$\begin{aligned} t_{1,2} &= \frac{t_0 F_{1,2}}{\Phi_{1,2} c_{1,2}} \left[\frac{\delta_{1,2} + b - (1 - 2a)c_{1,2}}{c_{1,2}\delta_{1,2}} \ln \frac{b + c_{1,2} + \delta_{1,2}}{b + c_{1,2} + \delta_{1,2} - 2bc_{1,2}} \right. \\ &\quad \left. + \frac{\delta_{1,2} - b + (1 - 2a)c_{1,2}}{c_{1,2}\delta_{1,2}} \ln \frac{b + c_{1,2} - \delta_{1,2}}{b + c_{1,2} - \delta_{1,2} - 2bc_{1,2}} - 2 \right]. \end{aligned} \quad (18)$$

Here

$$\begin{aligned} t_0 &= \frac{\mu_f L^2}{2k(P_f + P_c)}, \quad a = \frac{P_0}{P_f + P_c}, \quad b = \frac{\lambda}{1 + \lambda}, \\ c_{1,2} &= \frac{j_f L \Gamma_{1,2}}{(P_f + P_c) \Phi_{1,2}}, \quad \delta_{1,2} = \sqrt{(b - c_{1,2})^2 + 4bc_{1,2}}, \\ \Phi_1 &= F_1 = \Gamma_1 = 1, \quad \Phi_2 = \frac{1}{2} (\mu^* + 1), \end{aligned}$$

TABLE 1. Dependence of the Evacuation (τ , min) and Impregnation Times (t_2 , min) on the Magnitude of the Residual Pressure (P_0 , Pa)

τ	14	18	20	22	30	40	60
$P_0 \cdot 10^{-5}$	0,143	0,043	0,018	0,009	0,005	0,002	0,001
t_2	128,5	64,5	60,5	59,1	58,7	58,3	58,2

$$F_2 = \frac{1}{3}(\mu^{*2} + \mu^* + 1), \Gamma_2 = \frac{1}{6}(2\mu^*j^* + \mu^* + j^* + 2).$$

The quantity t_0 represents the impregnation time of the layer of a usual Newtonian liquid ($j = 0$) at constant temperature ($h = 0$) and complete evacuation ($P_0 = 0$). The impregnation time for arbitrary h satisfies the obvious inequality $t_1 \leq t \leq t_2$.

The maximum permissible value of P_0 is determined by the equality

$$a = \frac{1 - c_2}{1 + \lambda}, \quad (19)$$

for which t_2 becomes infinite. As an example, we shall present a calculation of the vacuum-forced impregnation of a layer of glass-micaceous cloth with the following data: $h = \infty$, $\lambda = 10$, $P_f = 3 \cdot 10^5$ Pa, $P_c = 0$, $L = 10^{-3}$ m, $k/\mu_f = 0.2 \cdot 10^{-14}$ m²/Pa·sec, $j_f = 3.4 \cdot 10^7$ Pa/m, $T_f = 60^\circ\text{C}$, $k/\mu_0 = 0.05 \cdot 10^{-14}$ m²/Pa·sec, $j_0 = 21.3 \cdot 10^7$ Pa, $T_0 = 30^\circ\text{C}$.

The maximum value of P_0 , according to (19), equals 0.144×10^5 Pa. The layer was evacuated in an autoclave with a volume of 1.2 m³ with the help of a type VN-4G vacuum pump with a capacity of 59 liters/sec. The air pressure was measured by a MTI manometer. The results of these measurements and the corresponding values of the impregnation time, determined according to Eq. (18), are presented in Table 1.

It follows from the table that the shortest time for the technological process being examined corresponds to a residual air pressure of $0.018 \cdot 10^5$ Pa and equals 80.5 min.

In conclusion, we note that the problem examined can be generalized to the case of continuous technological process of vacuum-forced impregnation, for which the heated porous layer enters into the impregnation chamber at a constant velocity. The impregnation of such a layer with the usual viscous liquid without taking into account the solubility of air was examined in [8].

NOTATION

v , percolation rate; P , compound pressure; P_c , capillary pressure; μ , viscosity of the compound; j , initial pressure gradient; k , permeability of the porous medium; T_0 , temperature of the porous medium before impregnation; T_f , temperature of the compound; θ , dimensionless temperature; κ , thermal conductivity of the compound; ξ , coordinate of the impregnation front; θ_ξ , P_ξ , m_ξ , V_ξ , temperature, pressure, mass, and volume of air, respectively, at $x = \xi$; μ_m , molecular air weight; R , universal gas constant; h , heat-transfer coefficient; t , impregnation time; $t_{1,2}$, impregnation time at $h = 0$ and $h = \infty$, respectively; τ , evacuation time.

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REFLECTANCE OF HEAT SHIELD MATERIALS UNDER
RADIANT-CONVECTIVE HEATING

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A procedure is presented for determining the spectral emissivity and surface temperature of heat shield materials subjected to radiant-convective heating by using the radiant component of the heat flux.

In order to determine the temperature of a surface and to calculate the heat balance, it is necessary to know the emittance of the material under investigation. It depends on many parameters, such as the properties of the material itself, the structure of the surface, the temperature, and the wavelength and direction of propagation of the radiation. Performing calculations which take account of the direction and wavelength dependence of the radiative characteristics of a material is a rather tedious process even when very large computers are used [1]. However, the reflection indicatrices of many heat shield materials correspond to diffuse radiation within an angle of $\sim 50^\circ$ from the normal to the working surface [2]. It was shown in [3] that the directional dependence of the optical properties of a surface must be taken into account only for specularly or nearly specularly reflecting surfaces, and that a simple model of diffuse reflection gives values which are in good agreement with a more detailed analysis and with existing experimental data.

It follows from the energy balance for an irradiated surface of an opaque material and Kirchhoff's law that

$$\rho(\lambda) = 1 - \varepsilon(\lambda),$$

from which the emittance of a surface can be found by using the reflection method [1, 4].

The measurement of the temperature of a surface subjected to radiant-convective heating requires taking account of or completely eliminating high fluxes of reflected radiation. This is commonly done by using choppers to separate the self- and reflected radiation from a surface [5]. The total intensity of the radiation from the sample surface is measured, and then while the incident radiation is cut off by the chopper, the intensity of the self-radiation from the material is measured. By measuring the intensity of the radiation reflected from the surface of a standard, the intensity of the radiation incident from the radiant heating source is determined. From these data and the formula for the heat balance, the reflectance of the surface of the material is

$$\rho(\lambda) = \frac{\beta_{\Sigma}(\lambda) - \beta_{\text{self}}(\lambda)}{\beta_0(\lambda)}, \quad (1)$$

where $\beta_{\Sigma}(\lambda) = \beta_{\text{self}}(\lambda) + \beta_{\text{refl}}(\lambda)$.

The true temperature of the surface is determined with a formula which follows from Wien's law:

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