IMPREGNATION OF A HEATED FILLER WITH A VISCOUS LIQUID

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The kinetics of the penetration of a viscous liquid (connecting) inside a preliminarily heated porous body (the filler) moving inside it is considered.

When manufacturing many composite materials employed in technology the process of impregnating a certain porous body, which plays the further role of a filler of the composite material, with a viscous liquid is widely employed. The viscous liquid later changes into a solid due to crystallization or vitrification on cooling, polymerization, etc. and plays the part of a solid binding matrix. The viscosity of the liquid, even at high temperatures, is often too high, and the filler is too dense so that the hydraulic resistance experienced by the liquid when filtering through the filler is also high, and when impregnating it is necessary to apply extremely high pressure gradients which cannot easily be employed under practical conditions. Prolonged heating of the liquid to comparatively high temperatures to reduce its viscosity is undesirable in view of possible thermal expansion of the liquid or acceleration of other physicochemical processes occurring in it, and reactions which would reduce the quality of the composite material obtained. Such a situation usually arises when making many thermoplastics, glass-plastic materials, and a number of other composite materials.

One of the methods of eliminating these difficulties is by preliminary heating to high temperatures of the filler itself for relatively moderate preliminary heating of the liquid. This enables one to confine the duration of the intense heating of the liquid within permissible limits, which considerably facilitates its penetration into the filler. Hence, it is necessary to consider heat conduction in the filler-liquid system and filtering of the liquid simultaneously, taking into account the nonlinear dependence of its viscosity on the temperature.

The specific system considered is shown in Fig. 1. It represents a realistic model of certain systems used in practice for producing composite materials. In the region of negative x the filler is heated in a gaseous medium under a pressure \( p' \) (often reduced compared with atmospheric pressure) to a temperature \( T' \), which may sometimes reach thousands or more degrees Centigrade. Hence, in region I of the filler, which may be a bunch of parallel fibers, a system of interlaced fibers, cloth material, etc., its pores are filled with gas under the pressure \( p' \). The filler is drawn with constant velocity \( u \) into the chamber II, filled with liquid at a temperature \( T'' < T' \) and a pressure \( p'' > p' \). Under the action of the pressure drop which occurs, the liquid, heated by heat transfer with the filler, penetrates deeper into it, displacing gas, and at distances \( x \geq L_x \) from the entry to the chamber II completely fills its pores. Thus, in addition to region I inside the filler there is a region III with pores filled with liquid; the boundary of the region is described by a certain function \( Y(x) \). The length of the working part of the apparatus \( L_x \) (where \( Y(L_x) = L_y \) ), its dependence on the various parameters of the process and the physical characteristics of the filler and liquid, and also possible methods of reducing this length while simultaneously increasing the rate of spread \( u \), which helps to intensify the process, are of particular practical interest.

In this paper we will only investigate the plane problem (a "strip" of filler is drawn, the transverse dimensions of which in the direction perpendicular to the plane of the figure is far greater than \( L_y \)), and we will assume that the penetrability of the filler, the density and specific heat of the material of the filler and liquid and also the effective thermal conductivities are independent of the pressure and temperature.
If the filler possesses a fine-pore structure, characterized by a high specific surface, we can assume that interphase heat and momentum exchange in region III occurs much more rapidly than the impregnation itself, so that when investigating the latter we can assume that the temperatures of the filler and the liquid at any physical point of this region are the same, while the component of the velocity of the liquid in the direction is simply the same as the drawing velocity $u$.

It follows from the equation of conservation of mass of the liquid $\frac{\partial v_y}{\partial y} = 0$ that the rate of filtering $v_y = v(x)$. On the basis of Darcy's law for the filtering of a liquid of variable viscosity, we have [1]

$$v(x) = -\frac{\alpha}{\mu(T)} \frac{\partial p(x, y)}{\partial y}. \tag{1}$$

The viscosity $\mu(T)$ depends on $x$ and $y$ implicitly in terms of the temperature dependence $T = T(x, y)$.

Integrating (1) and taking into account the fact that in regions I and II the pressure is $p'$ and $p''$, respectively, we obtain

$$p_0 = p'' - p' + p_c = \frac{v(x)}{\alpha} \int_0^{v(x)} \mu(T) \bigg|_{T=T(x, y)} dy, \tag{2}$$

where $p_c$ is the capillary pressure, consideration of which may be important when the pores of the filler are small [1].

From geometrical considerations we have for the function $Y(x)$

$$\frac{dY(x)}{dx} = \frac{v(x)}{eu}. \tag{3}$$

The equation of convective heat conduction in region III can be written, for the same temperatures of the phases, in the form (see [2])

$$\left[\frac{\partial}{\partial x} + (1-\varepsilon) \rho C_0 \frac{\partial T}{\partial x} + \rho C_v v(x) \frac{\partial T}{\partial y}\right] = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2}. \tag{4}$$

Generally speaking, the material is not necessarily isotropic, so that in general $\lambda_x \neq \lambda_y$. Practical methods of calculating these coefficients for heterogeneous materials of different structure can be found in [3]; the theory of the heat conduction of fiber materials, which are usually employed as fillers, is given in [4].

Equation (4) should, in the most general case, be solved simultaneously with similar equations written for regions I and II, under conditions of continuity of temperature and the normal component of the heat flux at the boundaries of the regions. Here, bearing in mind that we merely wish to obtain the simplest estimates, we will simplify the problem and we will only consider Eq. (4) for the boundary conditions

$$T = T', \ y = Y(x); \ T = T'', \ y = 0. \tag{5}$$

Hence, we have obtained the problem of heat conduction (4) and (5) in a region with unknown boundary $Y(x)$, defined by Eq. (3), for a strong nonlinear dependence of the coefficient $v(x)$ in (4) on the temperature, in accordance with Eq. (2).

It is not possible to solve such a complex problem directly in a complete formulation. We will therefore simplify the problem by assuming that in situations of particular practical