ISOTHERMAL FILLING OF A MOLDING CAVITY WITH SIMULTANEOUS IMPREGNATION OF A POROUS LAYER

A. V. Baranov and O. Kh. Dakhin

UDC 532.135:536.242.678:065

A study is made of isothermal filling of a planar cavity with a non-Newtonian fluid with simultaneous impregnation of a porous layer. The cavity flow is described by the inertialess Navier–Stokes equations, the porous layer flow by the Darcy equation, and the flow in the region adjoining the fluid–porous layer interface is described by the Brinkman equation.

Keywords: Newtonian liquid, shear flow, impregnation, molding.

We consider the process of low-pressure molding of reinforced or composite articles in closed molds. Owing to the use of relatively low-viscosity materials (various oligomers, resins, plastisols, etc.), molds are filled through narrow sprue channels at low pressures, which makes such processes energy-efficient. The process of filling a mold is accompanied by simultaneous impregnation of a porous (reinforcing) layer. Processes of this kind are used in the production of an enormous number of technical-, domestic-, and special-purpose products with various service properties. Upon completion of the processes of filling the mold and impregnation of the entire porous layer, the casting starts to solidify as a result of the processes of gelation of plastisols or chemical hardening of the polymeric binder (for example, epoxide and polyester resins). It is assumed in the present work that the processes of molding and impregnation are completed within the limits of the so-called induction period, i.e., prior to the onset of premature gelation or hardening.

A large number of works in the literature are devoted to modeling the processes of molding of composite articles in closed molds [1–3]. However, these publications consider injection of a polymer into molding cavities whose entire volume is occupied by some filler. Therefore the process of filling a cavity is only the process of porous material impregnation. In this case, the mathematical model is based, as a rule, on the Darcy law.

In the present work, however, we consider the filling of a cavity with simultaneous impregnation of a reinforcing porous layer according to the scheme shown in Fig. 1. The filling of a planar molding cavity of height $2h$ and length $l$ is made through a planar-slit sprue channel under constant pressure at the inlet $p_0$. The process of filling the cavity is accompanied by simultaneous impregnation of a reinforcing porous layer of thickness $H$. As the flow front moves in the planar cavity, the liquid medium propagates two-dimensionally through the porous medium with its own developing front. The works that describe liquid flow in channels whose one wall or both walls are porous (permeable) can be considered as analogous to our work [4–6]. However, all of these works examined a steady-state flow without the presence of any mobile impregnation front.

The most similar problem of casting molding of plastisols with impregnation of a fabric substrate was considered in [7, 8]. Assuming the fabric layer to be very thin, the authors of those works based their analysis on the approximation of "fast" impregnation of fabric. It was assumed that not the entire length $l$ of the fabric is impregnated but only a narrow zone adjoining the flow front in the cavity. The impregnation of fabric was considered to be one-dimensional and the pressure profile over the fabric depth to be linear. As a result of such assumptions it was obtained that the impregnation velocity is independent of the axial coordinate and that the mobile impregnation front is linear. The problem in [9] was staged and solved in a fuller formulation that is free of the constraints imposed in [7] and that covers a wide range of possible cases. The liquid flow in a planar cavity was described by the Navier–Stokes equation, and that in the porous layer by the Darcy equation. The solution was performed by a numerical method and interesting results of calculations of the impregnation front and pressure profile propagation in the cavity were presented for articles with a thin and a thick reinforcing layers. In subsequent works [10, 11] a similar problem was solved for an anisotropic porous layer. The considerable influence of the anisotropic...
permeability on the impregnation front development is shown. This topic underwent subsequent development in [12, 13]
where a nonisothermal problem had been formulated and solved with the viscosity dependent not only on temperature but
also on the degree of solidification of a polymeric binder. The substantial difference between the initial temperature of
the material and the temperature of the heated mold was the source of nonisothermicity. The calculations showed that the
preheating of a mold really reduces the impregnation time, but only in the case where one succeeds in carrying out the process
of molding within the induction period of the chemical solidification reaction.
Works [8–13] employed the same assumption on the presence of a discontinuity in shear stresses on the permeable
wall of a cavity. This was due to the fact that the shear flow in the cavity occurs with shear stresses that acquire maximum
values precisely on the channel walls. On the other hand, the use of the Darcy law for describing the impregnation process
means the absence of any shear stresses in the porous layer. It would have been more correct to use the Brinkman equation
[4, 5] that presupposes the presence, in the porous layer, of a certain transition zone (boundary layer) between the purely shear
flow in the channel and the so-called potential flow in the porous layer. The thickness of this boundary layer depends on the
hydrodynamic conditions of flow and porous body characteristics. However, the authors of those works intentionally made
this assumption in order to simplify the formulation and solution of the problem.
In this work we present a mathematical model of the process with the use of the Brinkman equation when the
condition of equality of not only the velocity but also of the shear stress is prescribed at the liquid–porous body interface.
An isothermal approximation of the problem is considered. The polymer is considered to be an incompressible Newtonian
liquid. Along with the neglect of the inertia effects, this allows one to describe the impregnation of the porous layer with the
aid of the Darcy law. It should be noted that the model developed can be applied not only to the flow scheme shown in Fig. 1.
With some very insignificant changes in the model, it can also describe the processes that follow the schemes shown in Fig. 2.

\[ Cavity \ flow: \ -2h \leq y \leq 0. \]  

Assuming the pressure in the cavity \( p_c \) to be independent of the transverse coordinate \( y \), we limit ourselves to one equation of motion:

\[ \frac{\mu}{\eta^2} \frac{\partial^2 u_c}{\partial y^2} = \frac{dp_c}{dx}, \]  

which is supplemented with the continuity equation

\[ \frac{\partial u_c}{\partial x} + \frac{\partial v_c}{\partial y} = 0. \]

The boundary conditions for the cavity flow are

\[ y = -2h, \quad u_c = v_c = 0; \]  

\[ y = 0, \quad u_c = u, \quad v_c = v, \quad \mu \frac{\partial u_c}{\partial y} = \eta \frac{\partial v}{\partial y}; \]

\[ x = 0, \quad \frac{p}{p_0} = \frac{h^2}{3\mu} \frac{p_0 - p_{0c}}{l_0}; \]