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ANALYTICAL MODEL FOR VACUUM INFUSION PROCESS

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VACUUM INFUSION

Vacuum Infusion (or VI) is widely used in different adaptations of LCM processes such as Vacuum Assisted Resin Transfer Molding (VARTM), Resin Film Infusion (RFI), and SCRIMP™ for low-cost manufacturing of large and high-quality composite structure.

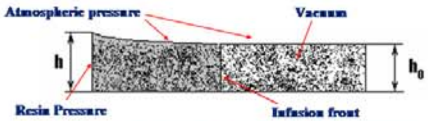


Figure 1. The thickness changes during the VI process.

The filtration of fluid in a porous material can be described in the fixed frame by the following exact system of equations:

$$\frac{\partial(\rho\varphi)}{\partial t}+\frac{\partial(\rho\varphi v_z)}{\partial z}+div_{\parallel}(\rho\varphi \mathbf{v}_{\parallel})=0$$

$$\mathbf{v}_{\parallel}=-\frac{\mathbf{K}_{\parallel}(\varphi)}{\mu}\nabla_{\parallel}p \qquad v_z=-\frac{K_z(\varphi)}{\mu}\frac{\partial p}{\partial z}$$

AVERAGING PROCEDURE

After integration of the continuity equation over the variable thickness of the layer h one has:

$$\int_0^{h(\mathbf{r},t)}\left(\partial_t\rho\varphi+\partial_z\rho\varphi v_z+div_{\parallel}\rho\varphi \mathbf{v}_{\parallel}\right)dz=$$
$$=\partial_t\left[h(\mathbf{r},t)\left(\frac{1}{h(\mathbf{r},t)}\int_0^{h(\mathbf{r},t)}\rho\varphi dz\right)\right]+div_{\parallel}\left[h(\mathbf{r},t)\left(\frac{1}{h(\mathbf{r},t)}\int_0^{h(\mathbf{r},t)}\rho\varphi \mathbf{v}_{\parallel}dz\right)\right]-$$
$$-(\rho\varphi)_{z=h}\left[\partial_t h(\mathbf{r},t)+\mathbf{v}_{\parallel z=h}\cdot\nabla_{\parallel}h(\mathbf{r},t)-v_{z z=h}\right]=0$$

The last term is equal to zero because of the free boundary condition:

$$\partial_t h(\mathbf{r},t)+\mathbf{v}_{\parallel z=h}\cdot\nabla_{\parallel}h(\mathbf{r},t)-v_{z z=h}=0$$

A similar averaging procedure can be applied to Darcy's Law. Finally we come to the next system of equations:

$$\partial_t h\varphi+div_{\parallel}h\rho\varphi\mathbf{v}_{\parallel}=0$$

$$\mathbf{v}_{\parallel}=-\frac{\mathbf{K}_{\parallel}}{\mu}\cdot\nabla_{\parallel}P$$

INCOMPRESSIBLE FLUID AND PREFORM MATERIAL

If the fluid and preform material are incompressible, the changes of the porosity are simply related to the deformation of the layer. In this case, the strain in the layer is:

$$\partial_t\varepsilon-div_{\parallel}\left((\varphi_0+\varepsilon)\frac{\mathbf{K}_{\parallel}(\varphi,\mathbf{r})}{\mu}\cdot\nabla_{\parallel}P\right)=0 \qquad \varepsilon=\frac{h-h_0}{h_0}$$

This is a complex non-linear parabolic equation. However, it is possible to show, that for practically real parameters (permeability, viscosity of fluid, etc.), the first (dynamic) term becomes negligibly small after several seconds or less. For this case, the equation above reduces to a elliptic-type non-linear equation:

$$div_{\parallel}\left(\mathbf{D}(\varphi(\varepsilon),\mathbf{r})\cdot\nabla_{\parallel}\varepsilon\right)=0$$

$$\mathbf{D}(\varepsilon,\mathbf{r})=(\varphi_0+\varepsilon)\frac{E\mathbf{K}_{\parallel}(\varphi,\mathbf{r})}{\mu}$$

1-D PROBLEM (A)

The evolution of the parabolic equation solution is defined by boundary and initial condition. The elliptic equation has no initial conditions. In order to make a choice between the infinite possible solutions of filtration with a moving boundary, one must incorporate additional information. In the general case, this is not a simple problem. It has real physical meaning: in 2- and 3-D cases, filtration of a viscous fluid (without surface tension) is unstable and close initial conditions lead in time to quite different solutions. However, in the 1-D case, the mass conservation law uniquely defines the solution.

1-D PROBLEM (B)

In the 1- D case, the filtration with a moving boundary can be formulated

$$\frac{d}{dx}\left(D(\varepsilon,x)\frac{d}{dx}\varepsilon\right)=0 \qquad \varphi=\frac{\varphi_0+\varepsilon}{1+\varepsilon}$$

The total mass conservation is

$$\int_0^t\varphi(0,t)h(0,t)v(0,t)dt=\int_0^{L(t)}\varphi(x,t)h(x,t)dx$$

These equations lead to one equation for $L(t)$, the position of the moving fluid front

$$J(t)=-\frac{I_0}{J^2(t)}\frac{d(J(t))}{dt} \qquad L(t)=-\frac{C(t)}{J(t)} \qquad \int_0^{\varepsilon_0(P(0,t))}D(\varepsilon)d\varepsilon=C(t)$$

The general solution for an arbitrary non-linear material is

$$\varepsilon(x,t)=F^{-1}\left(-\sqrt{\frac{I}{2t}}x+C(t)\right)$$

where I is defined by the $P(0,t)$.

1-D PROBLEM (Karman-Kozeni-Linear-Elastic Case)

Material parameters for a linear-elastic preform with Larman-Kozeni permeability are

$$E=Const. \qquad \hat{K}=k\frac{(1-v_f)^3}{(v_f)^2}$$

(The "physical" permeability, equal to porosity times the "engineering" permeability, is used here).

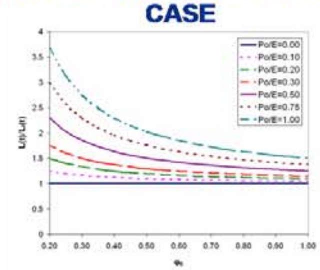
The position of the fluid front is then given by

$$L(t)=\sqrt{\frac{10kE}{16\mu(1-\varphi_0)^2}\frac{\left(\varphi_0+\frac{P_0}{E}\right)^4-(\varphi_0)^4}{\sqrt{\left(\varphi_0+\frac{P_0}{E}\right)^5-(\varphi_0)^5}}}\sqrt{t}$$

Distribution of strain

$$\varepsilon(x,t)=\left[\left(\left(\varphi_0+\frac{P_0}{E}\right)^4-\sqrt{\frac{16\mu(1-\varphi_0)^2}{10kE}}\sqrt{\left(\varphi_0+\frac{P_0}{E}\right)^5-(\varphi_0)^5}\frac{x}{\sqrt{t}}\right)^{\frac{1}{4}}-\varphi_0\right]$$

COMPARISON WITH INCOMPRESSIBLE PREFORM CASE



ACKNOWLEDGEMENTS

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