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Particles Deposit Formation and Filtering: Numerical Simulation in the Suspension Flow Through a Dual Scale Fibrous Media

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Summary: We present numerical simulation of particle filled resin flow through a fibrous medium taking into account dual scale porosity in LCM (Liquid Composite Molding) processes. During the flow, a strong interaction between the particle motion and the fluid flow takes place at the porous medium wall or at the fiber bundle surface. A model is developed to describe the particle deposition and filtering in the porous medium. In this study, the Stokes-Darcy equation is solved to describe the resin flow in a mesoscopic scale. The particle deposition mechanism is extensively studied taking into account the influences from such parameters as porous medium permeability, particle size and pressure drop. The mechanism leading to the accelerated or delayed filling is treated by analyzing the velocity filed around the fiber bundle surface. Finally, particle filtering simulation is performed for different particle loading levels to demonstrate the particle deposition and filtering mechanism during the composites manufacturing by LCM processes where the resin mixed with particles is injected into a fiber preform with dual scale porosity.

Keywords: deposit mechanism; dual scale porosity; filtration; particles interaction; particles

Introduction

For several decades, the modeling of particles transfer in a porous medium has attracted many authors for its importance in many applications, whether in the field of automotive, water treatment, environmental protection, oil exploration and the safety of retaining walls.

In the literature, there are two approaches to describe particles transfer in a porous medium, the macroscopic and microscopic approach. In general, the key issue is to better control the formation of deposits of solid particles on a porous surface.[6]

The objective of this work is to simulate the growth of a deposit on a porous surface, taking into account changes in the flow and geometry due to the presence of deposit. The calculation code used in this study is particularly suitable for treating this type of problem since the coupling of the Navier-Stokes (valid for a fluid sub-domain) and the Darcy model (valid for a porous sub-domain) is implemented. This article presents a model to study the effect of various physical parameters on the growth of a deposit.

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Modeling

Many studies have been devoted to understand and control the formation of the deposit of solid particles on collecting surfaces.[1] To analyze the initial phase of the formation of particle deposition on a porous surface filtration, a preliminary study was carried out in this work to determine the position of the particle deposited near a pore of the porous medium. Analysis of the mechanisms of filtration of particles and deposits during the impregnation of a fibrous medium with a charged resin is also conducted. The particle size in question is of the order of a few tens of microns.

Governing Equations of Motion in Dual Scale Porous Media

Equation of Motion in Wicks

As part of the flow of a resin (incompressible fluid) through a fibrous medium, the equation of conservation of mass is expressed by:

$$div\ (\mathbf{U}) = 0 \tag{1}$$

$\boldsymbol{U}$ is the flow velocity. At the macro-scale, this velocity can be related to the pressure field gradient P via Darcy's law:

$$U = -\frac{K}{\mu}\nabla P \tag{2}$$

μ is a fluid dynamic viscosity and K is the porous media permeability which can be estimated by Kozeny-Carman model:

$$K = \frac{D^2(1 - V_f)^3}{16 h_k {V_f}^2} \tag{3}$$

V_f is a fibers volume fraction, D is the fibers mean diameter, and h_k is the Kozeny constant.

Equation of Motion in the Canal between the Wicks

In the equation of mass conservation cited above (1), it is added the formulation of the conservation of momentum of the particles by the Stokes equation:

$$-\nabla P + \mu\nabla^2 U + \rho_f g = 0 \tag{4}$$

ρ_f is a fluid density and g is the gravity intensity.

Equation of Particles Motion

Many types of particles can be included in a liquid. The mass dynamics of these particles is governed by the equation:

$$\frac{du_p}{dt} = -\frac{1}{\rho_p}\nabla P + g + \beta(U - u')|U - u'|.\frac{\rho_f}{\rho_p} \tag{5}$$

$u' = u_p + u_{diff}$, and u_p, ρ_p and ρ_f are respectively the mean velocity, the particles and fluid density. U and P are the injected fluid velocity and pressure and β is the drag coefficient, u_{diff} the diffusion velocity of particles. The interactions between particles can be neglected.

Mathematical Model of Deposit

In the steady state in a saturated porous medium, the transport and deposit of the injected particles is described by equation (6) convection - dispersion including a kinetic term of particle deposit in the first order.[2]

$$\frac{\partial C}{\partial t} = D_L\frac{\partial^2 C}{\partial x^2} - \nu_p\frac{\partial C}{\partial x} - K_{dép}C \tag{6}$$

$K_{dép}$ Deposit kinetic coefficient (or particles adsorption), ν_p particles velocity, $\frac{\partial C}{\partial t}$ describes the temporal concentration variation of a coordinate point x, $D_L\frac{\partial^2 C}{\partial x^2}$ takes into account the effects of particle dispersion, $\nu_p\frac{\partial C}{\partial x}$ advection effects on the concentration for the same coordinate point x, and $K_{dép}C$ particles adsorption.

The Deposit kinetic coefficient $K_{dép}$ [s^{-1}] is a parameter characterizing the deposit velocity; its analytical expression is as follows:[4]

$$K_{dép} = \frac{3}{2}\frac{(1 - \phi)}{d_i}\nu_p\eta_c \tag{7}$$

ϕ is a media porosity, d_i is a capture surface parameter (pore or other) and η_i is an efficiency of this area (dimensionless parameter).

Efficiency of the capture surface is defined as the ratio between the deposit rate of particles on the surface and the total flux of particles. Then we write:

$$\eta_c = \frac{I_f}{UC\pi R_i^2} \tag{8}$$

where I_f is the particles deposit rate on the capture surfaces, U fluid velocity, C particles concentration in the suspension and R_i the capture area radius. Efficiency of this zone depends on the transport conditions. In (6), for instantaneous injection, the initial and boundary conditions are:

$$\left\{ \begin{array}{l} C(t=0,x)=0 \\ C(t,x=\infty)=0 \end{array} \right\}$$

Particle/Fluid Interaction

The movement of the particles is influenced by the flow of fluid through the drag forces. The opposite effect can be neglected because the forces acting on the fluid particle is small compared to other forces and inertia. The side effect of interaction is the displacement of fluid volume by the volume of particles. These effects are not taken into account in the model particles, so that the volume concentration of the particles is assumed to be small.

Numerical Approximations and Results

The set of evolution equations are considered solved by Eulerian approach coupled with the VOF method for tracking fluid interface [3] and a discretization by the finite element method.

Results of Simulation and Discussion

Many applications were realized taking into account this approach to simulate the resin flow in different configurations. First, resin flow without particles, second for one particle (for different: permeability, initial positions and sizes (diameter)) and finally, many particles filled resin flow.

A 2D geometry (Figure 1), initially full of air, is used to study flow in dual scale porosity. The jet is particle free. The model consists of two elliptical fiber tows, one in the center and the other in the corner (divided by four). The computational domain size account $\left(5\times10^{-3*}10^{-3}\right)[m]$ and the major and minor axes of the tows are respectively $\left(2.3\times10^{-3*}2.5\times10^{-4}\right)[m]$. The discretization is carried out by a Cartesian rectangular finite element mesh. The specific radius of fiber filaments is assumed $R_f=2.3\times10^{-5}[m]$, a porosity $\phi=0.53$ and the permeability of the tows is estimated as $K_P=1.1718\times10^{-11}[m^2]$. In this application, we use the resin Epoxy with viscosity 0.1 [Pa.s] that seeps into by the upper side and out through lower face. The difference pressure is $10^4[Pa]$ between the upper and lower boundaries. For the other, the wall boundary conditions are applicated.

Figure 2 shows dynamic flow of epoxy resin in the end of injection in the RTM process (without particles) for three different permeability values: from $1.1718\times10^{-10}[m^2]to1.1718\times10^{-12}[m^2]$. Clearly shows varied aspects at the end of injection, due to the different permeability in terms of suitability for passing there through the reference fluid under the effect of the pressure gradient in the fibrous medium, which generates a pressure drop during the fluid flow through this last.

Analysis of Particles Deposit : A Single Particle Case

In this section, we are interested in the deposit of a single particle on the porous surface. The diameter of particle is $d=40[\mu m]$, it is placed initially at $(X,Y)=$

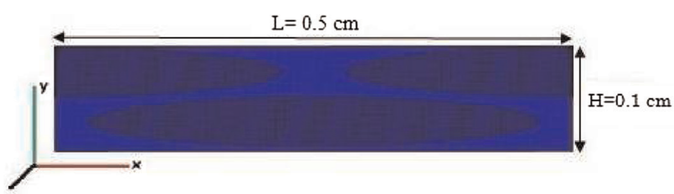

Figure 1.
A sketch of a model dual scale porous media with two elliptic fibers tows.

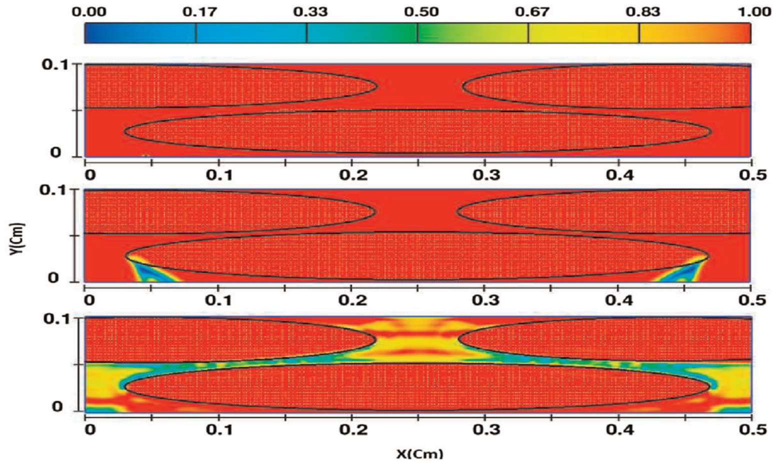

Figure 2.
Dynamic flow of the epoxy resin in the end of injection through RTM (without particles) for three different permeability values in the range of: (from top to bottom) $K_1 = 1.1718 \times 10^{-10} [m^2]$, $K_2 = K_1/10$ and $K_3 = K_1/100$.

$(1.59 \times 10^{-3}, 5.64 \times 10^{-4})\,[m]$ in the first case and at $(X, Y) = (2.51 \times 10^{-3}, 6.3 \times 10^{-4})\,[m]$ in the last.

Figure 3 describes the trajectory of a particle, for three values of permeability. Note that the particle deposit is delayed or advanced by the permeability of the media, more its value decreases, more the deposit is lagged or not seen in the very low permeability media case. Then, in the presence of a very low permeability surface, the media is considered blocked and therefore any particle injected will follow the preferential path of transport available without accumulating or being captured. Such behavior is also observed (Figure 5), where we note that the flow velocity near the particle decreases if the surface is not very permeable. For a low permeability surface, the deposit is significantly delayed due to the hydrodynamic force which becomes repulsive.

We proceed to a second test (Figure 4), and this time by setting the particle near the center of the central wick at $(X, Y) = (2.51 \times 10^{-3}, 6.3 \times 10^{-4})\,[m]$. As previously obtained and significantly, the deposit of particles is delayed or does not exist depending on the porous medium nature. In both cases where the surface has a permeability of about $\sim 10^{-10} et \sim 10^{-11} [m^2]$ the particle is deposited at almost the same place.

However, for the surface permeability $\sim 10^{-12}[m^2]$, the particle moves away to avoid a disruption that occurs during its passage and deposited further the surface

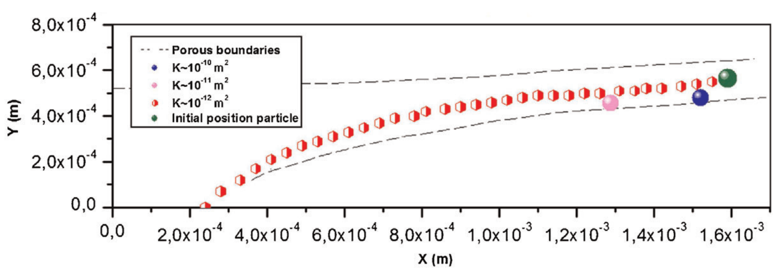

Figure 3.
Trajectory of particle initially positioned at $(X, Y) = (1.59 \times 10^{-3}, 5.64 \times 10^{-4})\,[m]$ until deposit, for three permeability values.

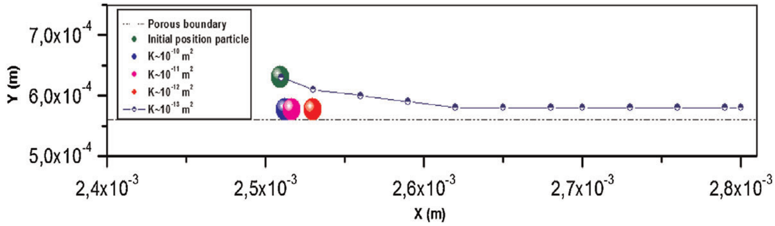

Figure 4.
Trajectory of particle initially positioned at $(X, Y) = (2.51 \times 10^{-3}, 6.3 \times 10^{-4})\,[m]$ until deposit, for four permeability values.

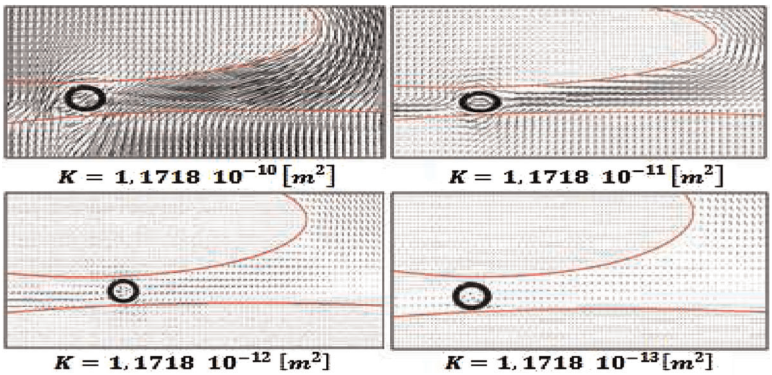

Figure 5.
The velocity field around a particle for four permeability values [m^2].

finally. This disturbance is due to the velocity field (Figure 5) produced by the flow. Finally, in the case of a very low permeability surface ($K \sim 10^{-13}[m^2]$), the particle follows a definite path without deposit.

Pressure Field and Effect of Particle Size on the Deposit

Figure 6 shows the effect of particle size on the deposit. Note that the deposit is carried out for all particle sizes and a large particle is deposited faster than small one.

The passage of the suspension through the cake (particles deposited on the filter) and the filter medium is accompanied by a pressure drop equal to a pressure difference between upstream and downstream. As indicated by the Poiseuille law, the flow rate is directly proportional to the pressure drop along the media and on the surface of the

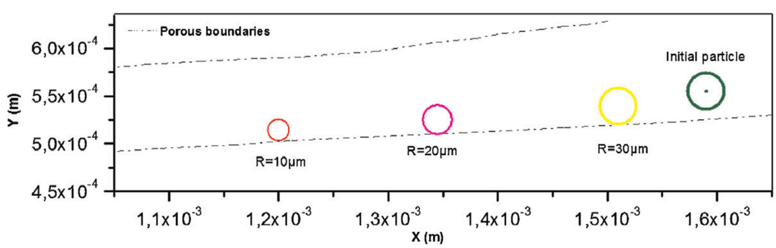

Figure 6.
Effect of particle size (10, 20 et 30 μm) on the deposit, initially positioned at $(X, Y) = (1.59 \times 10^{-3}, 5.64 \times 10^{-4})\,[m]$ for $K = 1.1718 \times 10^{-11}[m^2]$.

porous bed (filter), inversely proportional to the dynamic viscosity of the suspension injected and to the thickness of the porous bed via the characteristic parameter of the fibrous (porous) medium permeability.

For this type of filtration (with deposit), the result of (Figure 7) gives us an early and rapid pressure that increasing with low permeability $\sim 10^{-12}$) and a slight increase in the case of a high permeability medium. We also see (Figure 6) that the small particle is deposited more slowly than high, since the latter affects the porous surface faster. There is no effect of pressure until the deposit; the time of filtration and the filtrate volume collected are the two variables influencing particle transport. The deposition time is inversely proportional to the pressure drop: $t_{dép} = 1/\Delta P$; pressure and permeability vary by the properties of the porous surface whose saturation and overstressing affecting the porosity and interconnectivity between the pores. Indeed, more the pore diameter is smaller, more speed and pressure gradients are important. This is also due to the varying viscosity of the suspension and the friction between the channels, the resistance of the filter, the resistances of the cake and to movement of the fluid.[5]

Filtration and Deposit of Particles

A VER Case (Representative Elementary Volume)

With the same data used previously, and permeability $K = 1.1718 \times 10^{-11}[m^2]$ we inject 500 particles with diameter $20[\mu m]$ by a pressure gradient $\Delta P = 10^3[Pa]$ between the upper and lower boundaries. The above Figure 8 describes the particle distribution obtained by numerical simulation of two: filtration and deposit mechanisms. In this case, we note that most of the

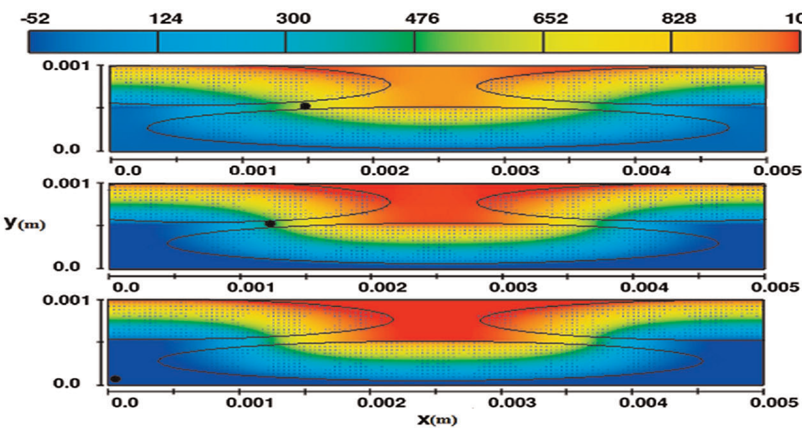

Figure 7.
The pressure profile (in [Pa]) for three different permeability values in the range of: (from top to bottom) $K_1 = 1.1718 \times 10^{-10}[m^2]$, $K_2 = K_1/10$, $K_3 = K_1/100$.

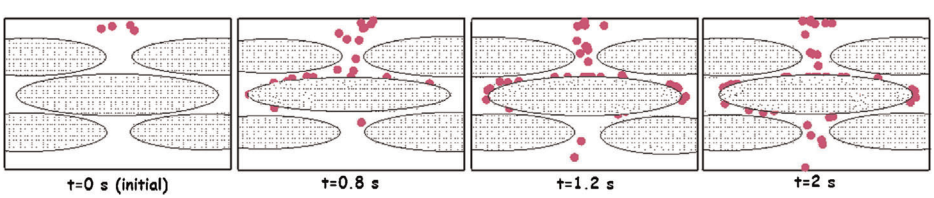

Figure 8.
Distribution of particles in fibrous dual scale media during filtration and deposit (VER case).

particles are deposited in the center of the fiber surface.

Injection RTM Case

In this study, we look at injecting a particles filled resin on a new geometry (Figure 9) of a dual scale fibrous porous medium with permeability $K = 10^{-14}[m^2]$ and porosity $\phi = 0.4$. We consider a constant flow rate $Q_{inj} = 7 \times 10^{-11}[m^3/s]$. Viscosity of resin $\mu = 0.1[Pa.s]$, size of particles $d = 12[\mu m]$ (by 48%).

Figure 10, shows the distribution of the particles during that injection. We observe a high concentration of particles in the channels in the middle of the preform where the flow velocity is low. While a small amount of particles infiltrates without deposit or deposits on the surface of the wick. The deposition of particles from the center of the surface of the wick is explained by the fact that the flow in this area is significantly accelerated, due to the effect of blocking particles already deposited in the center which weakens the local permeability. Thereafter at the end of injection, the deposited particles then form a single layer over the surface of the fibrous wicks.

Conclusion

In this work, we present a numerical tool in simulating the particle deposition in dual-scale porous media, especially adapted for

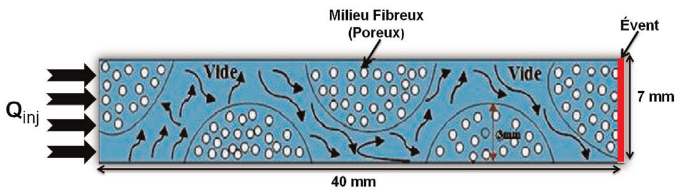

Figure 9.
Sketch of the injection of particles filled resin.

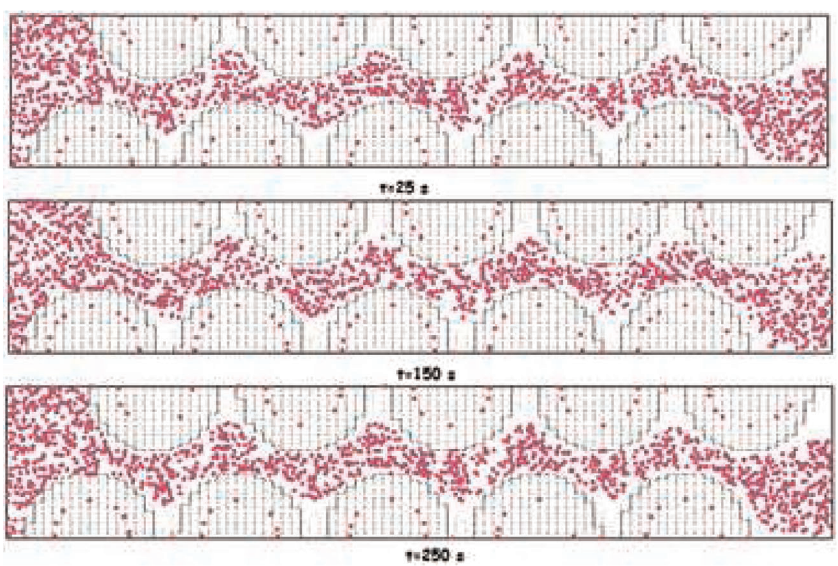

Figure 10.
Distribution of particles in the fiber preform (dual scale) during the injection.

the LCM process. The formation of a deposit of particles is a function of complex forces acting on the particle and having an impact on particle interactions - fluid particle - wall and particle - particle. Prior knowledge of certain characteristics of the particles allows, a priori, assessing the influence of certain forces in question. In general, the key issue is to better control the formation of deposits of solid particles on a porous surface.

In addition, the capture of particles depends on the physico-chemical conditions existing, acting both on the surface charges of the particles and the porous medium. We consider the particle–fluid hydrodynamic interaction, the particle deposition onto the permeable surface, at the individual particle level, and addressed it with the coupled dual-scale flow. The coupled flow in dual scale porous media is treated by the Stokes–Brinkman coupling with the Volume – Of - fluid (VOF) method. To treat the effects of the permeability, the single particle deposition was observed. We realize that particle deposition is enhanced in the highly permeable media by two mechanisms. One is the penetrating flow into the porous tow and the second is the formation of the downward flow due to the deposit of the particle near the surface. Another simulation was carried out with a large number of particles to support the previous scheme to address the both, particle filtration and deposition in LCM. For this, a parametric study was realized: effects of permeability, the particle size, particle concentration, etc. which is of great significance in manufacturing composite materials.

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