Simulation of deposition and filtering of particle in the resin flow through a dual scale porous medium

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Abstract

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 field 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: Particles – deposit mechanism – fluid-particles interaction – dual porosity – filtration.

1. 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. 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.

2. 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.

2.1 Governing equations of motion in dual scale porous media

2.1.1 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:

\[ \text{div} \ U = 0 \]  
\[ U \] is the flow velocity. At the macro-scale, this velocity can be related to the pressure field gradient \( P \) via Darcy’s law:

\[ U = -\frac{K}{\mu} \nabla P \]  
\( \mu \) is a fluid dynamic viscosity and \( K \) is the porous media permeability which can be estimated by Kozeny-Carman model:

\[ K = \frac{D^2(1 - V_f)^3}{16h_kV_f^2} \]  
\( V_f \) is a fibers volume fraction, \( D \) is the fibers mean diameter, et \( h_k \) is the Kozeny constant.

2.1.2 Equation of motion in the canal between the wicks

In the equation of mass conservation cited above (2.1), it is added the formulation of the conservation of momentum of the particles by the Stokes equation:

\[ -\nabla P + \mu \nabla^2 U + \rho_f g = 0 \]  
\( \rho_f \) is a fluid density and \( g \) is the gravity intensity.

2.1.3 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:

\[ \frac{du_p}{dt} = -\frac{1}{\rho_p} \nabla P + g + \beta \left( U - u' \right) \ \text{U} - u' \cdot \frac{\rho_f}{\rho_p} \]  
\( u' = u_p + u_{diff} \), and \( u_p, \rho_p \) et \( \rho_f \) are respectively the mean velocity, the particles and fluid density. \( U \) and \( P \) are the injected fluid velocity and pressure and \( \beta \) is the drag coefficient, \( u_{diff} \) the diffusion velocity of particles. The interactions between particles can be neglected.

2.2 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 (2.6) convection - dispersion including a kinetic term of particle deposit in the first order [2].
\[
\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v_p \frac{\partial C}{\partial x} - K_{dep} C
\]  
(2.6)

$K_{dep}$ Deposit kinetic coefficient (or particles adsorption), $v_p$ 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, $v_p \frac{\partial C}{\partial x}$ advection effects on the concentration for the same coordinate point $x$, and $K_{dep} C$ particles adsorption.

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

\[
K_{dep} = \frac{3}{2} \frac{1 - \phi}{d_i} v_p \eta_c 
\]  
(2.7)

$\phi$ is a media porosity, $d_i$ is a capture surface parameter (pore or other) and $\eta_c$ 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:

\[
\eta_c = \frac{I_f}{UCnR_i^2} 
\]  
(2.8)

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 (2.6), for instantaneous injection, the initial and boundary conditions are:

\[
C, \ t = 0, x = 0 \\
C, \ t, x = \infty = 0 
\]  
(2.9)

2.3 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.

3. Numerical approximations

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.

4. Numerical results – Simulation

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.

FIG. 4.1 – A sketch of a model dual scale porous media with two elliptic fibers tows
A 2D geometry (FIG. 4.1), 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 accounts 5.10^{-3} \times 10^{-3} m and the major and minor axes of the tows are respectively 2.3.10^{-3} \times 2.5.10^{-4} m. The discretization is carried out by a Cartesian rectangular finite element mesh. The specific radius of fiber filaments is assumed \( R_f = 2.3.10^{-5} \) [m], a porosity \( \phi = 0.53 \) and the permeability of the tows is estimated as \( K_p = 1.1718.10^{-11} [m^2] \). 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 10^1[Pa] between the upper and lower boundaries. For the other, the wall boundary conditions are applied.

Figure (4.2) shows dynamic flow of epoxy resin in the end of injection in the RTM process (without particles) for three different permeability values: from \( 1.1718.10^{-10} m^2 \) to \( 1.1718.10^{-12} m^2 \). 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.

**FIG. 4.2 – 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) K1= 1.1718.10^{-10} m^2 K2= K1/10, K3=K1/100.**

### 4.1 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 \( X,Y = 1.59.10^{-3},5.64.10^{-4} \) m in the first case and at \( X,Y = 2.51.10^{-3},6.3.10^{-4} \) m in the last.

**FIG. 4.3 – Trajectory of particle initially positioned at X,Y = 1.59.10^{-3},5.64.10^{-4} m until deposit, for three permeability values**

FIG (4.3) 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 4.5), 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, and this time by setting the particle near the center of the central wick at \( X, Y = 2,51.10^{-3}, 6.3.10^{-4} \) 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 \(~10^{-10} \) et \(~10^{-11} \) m² the particle is deposited at almost the same place. However, for the surface permeability \(~10^{-12} \) m², the particle moves away to avoid a disruption that occurs during its passage and deposited further the surface finally. This disturbance is due to the velocity field (Fig. 4.5) produced by the flow. Finally, in the case of a very low permeability surface \((K \sim 10^{-13} \) m²\), the particle follows a definite path without deposit.

![Figure 4.5](image)

**FIG. 4.5** – The velocity field around a particle for four permeability values.

### 4.2 Effect of particle size on the deposit

![Figure 4.6](image)

**FIG. 4.6** – Effect of particle size (10, 20 et 30 µm) on the deposit, initially positioned at \( X, Y = 1,59.10^{-3}, 5,64.10^{-4} \) m for \( K = 1,1718.10^{-11} \) m².

Figure (4.6) 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.

### 4.3 Filtration and deposit of particles

#### 4.3.1 A VER case (Representative Elementary Volume)

![Figure 4.7](image)

**FIG. 4.7** – Distribution of particles in a VER of a fibrous dual scale porous media during filtration and deposit.
With the same data used previously, and permeability \( K = 1,1718 \cdot 10^{-11} \text{ m}^2 \) we inject 500 particles with diameter 20 \( \mu \text{m} \) by a pressure gradient \( \Delta P = 10^3 \text{ Pa} \) between the upper and lower boundaries. The above figure (4.7) describes the particle distribution obtained by numerical simulation of two: filtration and deposit mechanisms. In this case, we note that most of the particles are deposited in the center of the fiber surface.

### 4.3.2 Injection RTM case

![FIG. 4.8 – Sketch of the injection of particles filled resin](image1)

**FIG. 4.8** – Sketch of the injection of particles filled resin

![FIG. 4.9 – Distribution of particles in the fiber preform (dual scale) during the injection](image2)

**FIG. 4.9** – Distribution of particles in the fiber preform (dual scale) during the injection

In this study, we look at injecting a particles filled resin on a new geometry (Fig. 4.8) of a dual scale fibrous porous medium with permeability \( K = 10^{-14} \text{ m}^2 \) and porosity \( \phi = 0.4 \). We consider a constant flow rate \( Q_{\text{inj}} = 7.1 \cdot 10^{-11} \text{ m}^3 \text{ s}^{-1} \). Viscosity of resin \( \mu = 0.1 \text{ Pa s} \), size of particles \( d = 12 \mu \text{m} \) (by 48\%). Figure (4.9), 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.

### References


