ON THE OBSERVATION OF FLOW FRONT POSITION UNDER DISCONTINUOUS INLET PRESSURE

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Abstract
This paper describes the influence of variable inlet pressure on the flow front position and velocities in a one dimensional vacuum infusion process. To do so, a set of experiments was carried out at INEGI's Vacuum Infusion Laboratorial System, using epoxy resin and a random glass fibre mat. These experiments were devised to capture the influence of several variables of interest in this phenomena. The observed data was obtained by pressure sensors, to measure the pressure at relevant locations and a digital video camera to detect the flow front position at each time instant. The data shows a dynamical behaviour of the infusion process that cannot be modelled using the traditional quasi-steady-state equations. Hence, there is a need to consider relevant dynamical phenomena like capillary pressure and nonlinear pressure gradient inside the fluid. The analysis of the obtained data reveals the relative influence of the various phenomena and provides critical information for the subsequent modelling attempts. A system identification approach was performed to fit a linear dynamical system to each of the infusion process phases. The non-linear nature of vacuum infusion processes, as they are ruled by the Darcy's law, optimal approximations in the Least Squares sense were obtained. The study of these phenomena is expected to provide further insight on the dynamical behaviour of vacuum infusion processes with direct implications on the dynamical models that can be used for real-time control of such industrial processes.

1. Introduction

The most relevant concepts regarding the flow of a fluid through a porous medium and the modelling techniques for vacuum infusion process will now be presented to support the developments of the following sections.

1.1 Fluid flow through posous media

Typical modeling strategies [1][2] for vacuum infusion processes are based on the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{u}) = 0 \Leftrightarrow \frac{\partial \rho}{\partial t} + \frac{\rho \partial u}{\partial x} + \frac{\rho \partial v}{\partial y} + \frac{\rho \partial w}{\partial z} = 0 \tag{1}$$

Where:

ρ - Density;
$\vec{u}$ - velocity vector.

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And on the Darcy's Law:

$$\{\vec{U}_D\} = -\frac{1}{\mu}[K].\nabla P \Leftrightarrow \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix} = -\frac{1}{\mu}\begin{pmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{pmatrix}\begin{pmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \\ \frac{\partial P}{\partial z} \end{pmatrix} \quad (2)$$

Where:

$\vec{U}_D$ - *Darcy's* velocity vector;
μ - Fluid viscosity;
[K] – Permeability matrix of the porous medium;
P – Pressure.

These are the equations that describe general physical concepts like mass conservation and the flow of a fluid through porous media. Equations (Eq. 1) and (Eq. 2) describe these phenomena in a general 3D setting and are often simplified into the 2D or 1D cases.

To develop a mathematical model to describe a specific setup where a fliud flows through a porous media, (Eqs. 1 and 2) must be solved for given initial and boundary conditions. Unfortunatelly, the solution cannot be analytically derived in most cases and computational methods are usually required. Further, the permeability of the porous media cannot be precisely defined and a statistical representation is usualy required.

1.2 Modelling a vacuum infusion process

When modelling a vacuum infusion process, there are thee main phenomena that must addressed; the resin flow, the compaction of the porous media and the resin cure. These three phenomena are interconnected and cannot be analysed independently. However, some approximations are usually considered to simplify the models without loosing the physical coherence. The considered simplifications and the modelling approach are strictly dependent on the application.

Here, the objective is to develop a model that captures the dynamics of the resin flow front as it wets the porous medium, including the response to variable pressure differences between the inlet and the vacuum caused by the actuation of an "on/off" inlet valve. The developed models must be simple enough to be used in real-time process monitoring and control applications.

The simplicity requirement implies the use of analytical solutions that are approximations of the real phenomena, but are still able to capture the most relevant dynamics.

Analytical approximations of the fluid flow through porous media has already been addressed by several authors [1][2][3], but the models are only applied to free-flow infusions, where the inlet and vacuum valves are open from the beginning to the end of the process and the resin flows freely through the porous media.

Some authors addressed the process control issue [4][5], improving the existing models towards a real-time application with the objective of reducing the dry spots in the fibres. The present study aims at controlling the flow front position, but also its speed to minimize the void formation inside the porous media.

A 1D approach is considered for this study to allow a consintent focus on the relevant phenomena.

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2. Experimental Setup

The following experimental setup is installed at INEGI, Composite Materials Laboratory, and was designed to capture the most relevant phenomena in a vacuum infusion process.

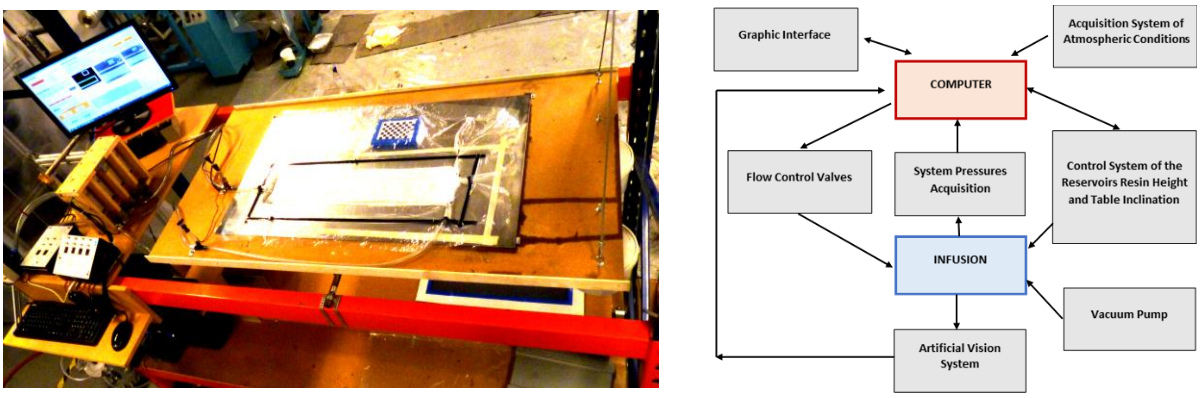

Figure 1. Experimental setup installed at INEGI (left: picture ; right: schematic description).

The present study will be focused on the effect of the pressure difference from the inlet to the vacuum outlet on the one dimensional flow front position and velocity.
Therefore, the components of the experimental setup relevant for the present study are:

1) the webcam, that captures the flow front position.
2) The “on/off” inlet valve, that controls the resin flow into the infusion.
3) The inlet pressure sensor.
4) The vaccum pressure sensor.

All the generated information is gathered by the central computer and can be used for the subsequent system identification algorithms.

3. Modelling

The modelling methodology is now presented and followed by the actual modelling of the various relevant dynamics.

3.1. Modelling methodology

The number of relevant physical phenomena in a vacuum infusion process makes the phenomenological modelling approach too complex, while their stochastic nature would render the model parameters too vague and phycically meaningless. The adopted methodology will start from the simpler model possible, viscous flow through porous media in a free-flowing infusion and then, the influence of the inlet “on-off” valve actuation is modelled through increasingly complex models that include more physical phenomena, like the non-linearity of the pressure field or the capillary pressure.

3.2. Free-flow infusion

In a free-flowing infusion, where the inlet valve is kept open during the whole run, the flow front dynamics can be modelled by the Darcy’s law:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\frac{k}{\mu\phi} \cdot \frac{\mathrm{d}p}{\mathrm{d}x} \tag{3}$$

The integration of the Darcy's law yields the following dynamics for the flow front position, considering that the flow front starts at position $x_{ff}(0) = 0$:

$$x_{ff}(t) = \sqrt{2 \cdot \frac{k}{\mu \cdot \phi} \cdot \Delta\mathrm{P} \cdot \sqrt{t}} \tag{4}$$

$$x_{ff}(t) = \sqrt{2 \cdot \mathrm{C} \cdot \Delta\mathrm{P}} \cdot \sqrt{t} \tag{5}$$

$$C = \sqrt{\frac{k}{\mu \cdot \phi}} \tag{6}$$

$$\Delta\mathrm{P} = P_{inlet} - P_{vacuum} \tag{7}$$

The constant C includes the effect of the porous medium permeability k and porosity ϕ and, the fluid viscosity μ which. C can be estimated from the gathered flow front position data presented in the following figure. This figure also includes some faulty measurements removed from the data set and the simulated flow front evolution considering the estimated C constant and a constant pressure difference between the inlet and the vacuum.

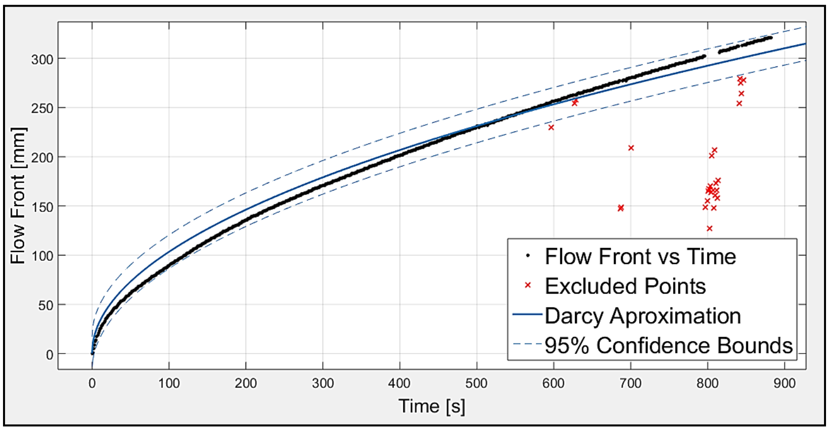

Figure 2. Flow front position from a free-flow infusion, including the estimated dynamics.

The estimated constant:

$$C = 0.5434 \pm 0.2340 \left[\frac{mm^2}{kPa{\cdot}s^2}\right] \tag{8}$$

With mean 0.5434 and standard deviation 0.2340.

3.3. Inlet valve closing dynamics

The flow front dynamics will now be analysed in the case where the inlet valve is opened and closed during the infusion, as shown in figure 3. These actions will unveil the presence of other physical phenomena that are typically neglected and absorbed by the stochasticity of the flow process. Several modelling attempts will now be carried out, trying to detect and estimate the parameters of these phenomena.

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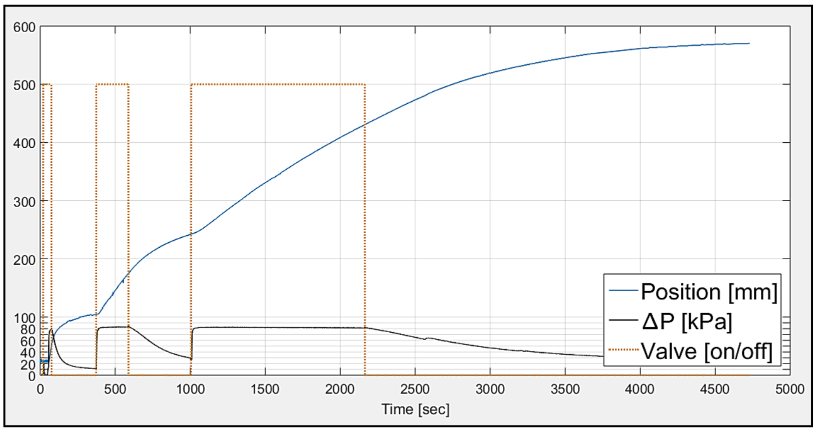

Figure 3. Infusion with actuation of the “on-off” inlet valve.

3.1.1 Darcy’s Law with linear pressure gradient

The model identified in the previou section 3.2 will now be applied to the infusion described in figure 3. The estimated evolution is presented in red in figure 4, where significant deviations occur. Even if one selects $C = 0.7$, the deviations are reduced but it becomes clear that some phenomena is not being taken into account.

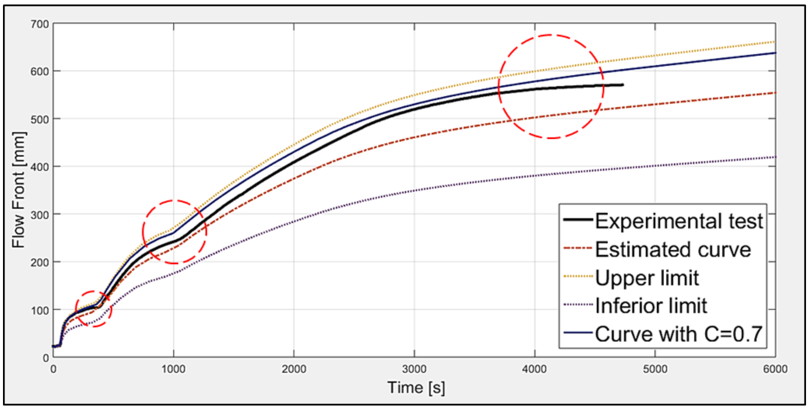

Figure 4. Flow front position, including the estimated dynamics considering the Darcy’s Law with a linear pressure gradient.

3.1.2 Darcy’s Law with linear pressure gradient and capillar pressure

A closer analysis of figure 3 shows that, when the inlet valve is closed, the inlet pressure does not tend to the vacuum pressure and therefore a persistent pressure difference exists when the infusion is let running until the process is stabilized. This pressistent pressure difference was measured to be around 8kPa and independent of the flow-front position. According to [1], this pressistent pressure difference can be considered as a capillar pressure and the pressure difference ΔP must be compensated accordingly:

$$\Delta \mathrm{P} = P_{inlet} - P_{vacuum} - P_{capillar} \tag{9}$$

The estimated flow front evolution considering this capillary pressure is described in the following figure 5:

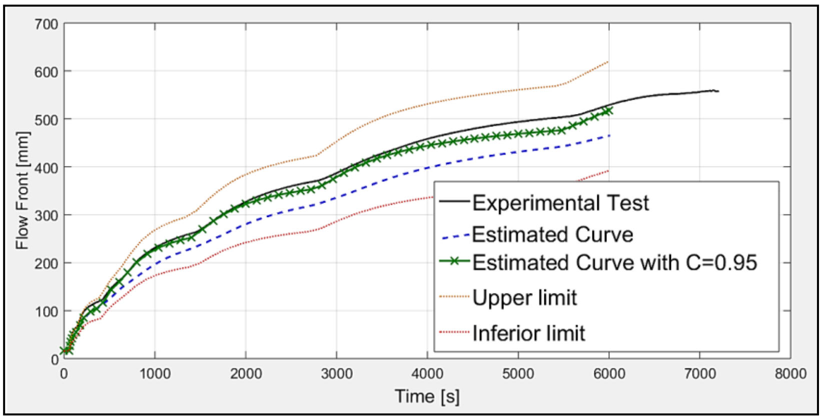

Figure 5. Flow front position, including the estimated dynamics considering the Darcy's Law with a linear pressure gradient and a 8kPa capillary pressure.

3.1.3 Darcy's Law with non-linear pressure gradient and capillar pressure

The model obtained in the previous section still shows a substantial discrepancy from the experimental data. Several authors reported the non-linearity of the pressure gradient inside the fluid flowing through the porous media. [4] approximated this gradient by a quadratic function and obtained considerably good results when compared with the experimental data. This approach will also be followed here to further approximate the experimental data from figure 3.

According to [4], this nonlinearity must be added to (Eq. 9) as a nonlinear compensation f_P:

$$\Delta P = P_{inlet} - P_{vacuum} - P_{capillar} - f_P \tag{10}$$

The nonlinear compensation was obtained form the experimental data from various infusions, presented in the following figure:

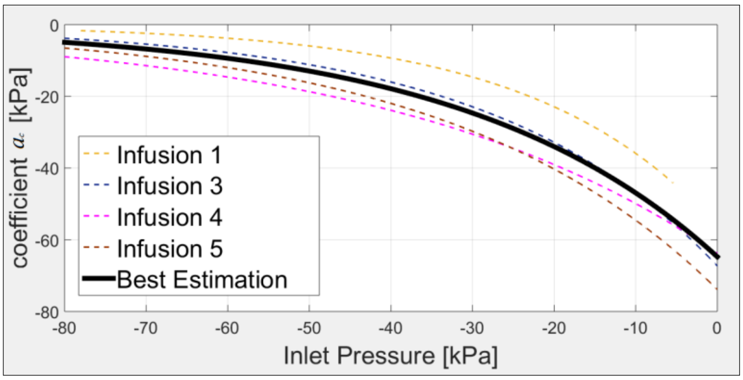

Figure 6. Exponential approximation of the nonlinear pressure gradient.

The obtained compensation f_P is:

$$f_P = a.e^{b.P_{inlet}}$$

With: (10)

$$a = -64.75 \quad , \quad b = 0.03218$$

The estimated flow front evolution considering the capillary pressure and the nonlinear pressure gradient is described in the following figure 7:

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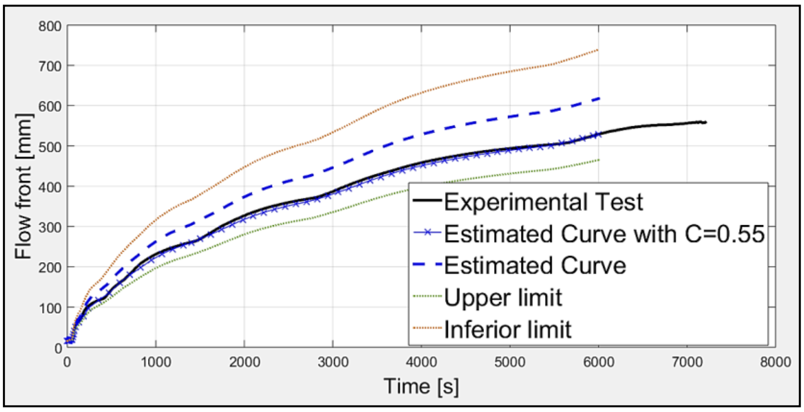

Figure 7. Flow front position, including the estimated dynamics considering the Darcy's Law with a non-linear pressure gradient and a 8kPa capillary pressure.

3.4. Comparison of the various modelling approaches

The simulations from all modelling approaches are presented in the following figure.

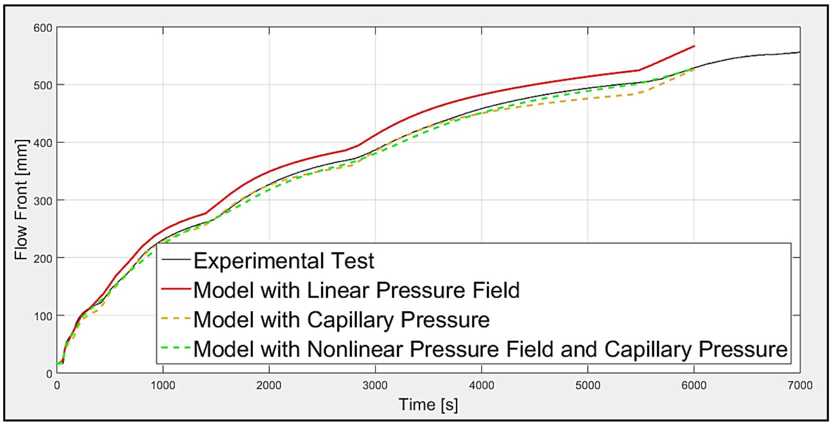

Figure 8. Flow front position, from all modelling aproaches.

The following table shows the Mean Squared Error (MSE) from all thee simulations to show the quality of the approximations:

Table 1. Mean Squared Error of all modelling aproaches.

Linear pressure gradient	Capillar pressure and linear pressure gradient	Capillar pressure and nonlinear pressure gradient
402.2	111.6	28.9

From figure 8 and table 1 is clear that the model that considers the capillary pressure and the nonlinear pressure gradient in the fluid is the most accurate.

3.4. Inlet valve opening dynamics

The inlet pressure dynamics when the inlet valve is opened presents a very fast response, when compared with the rest of the relevant dynamics, as can be seen in figure 2 with inlet valve openings at instants aproximatelly 20s, 350s and 1000s. From the presented data, the pressure difference dynamics was approximated by a first order system with time constant estimated to be 5 s^{-1}.

3.6. Validation

A new experiment was run to produce data to validate the developed model that considers the capillary pressure and the nonlinear pressure gradient. The results show a good coherence between the simulation and experimental data.

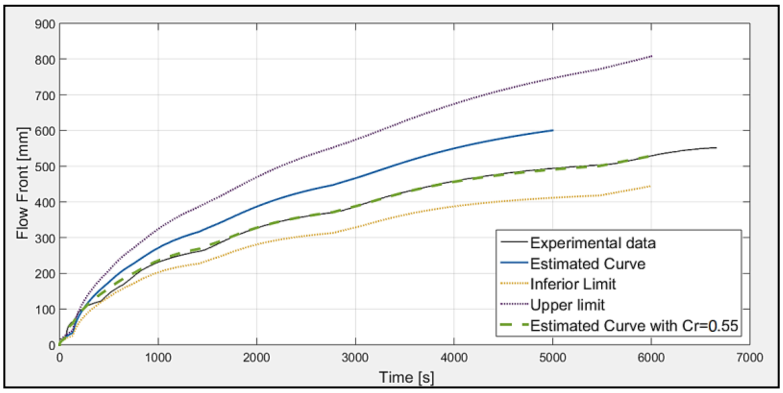

Figure 9. Flow front position, validation run for the considering the model that considers the Darcy's Law with a non-linear pressure gradient and a 8kPa capillary pressure.

4. Conclusions

The modelling approach showed that good analytical models can be developed to simulate vacuum infusion processes, even when the pressure difference between the resin inlet and the vacuum is not constant. The traditional darcy law must be augmented with capillary pressure and the pressure gradient in the fluid must be approximated by a nonlinear function.
The present study showed that the derived analytical for the 1D case are simple enough to be used in real-time applications with a good accuracy.
The authors reflect that other simplifications may be used in terms of phenomena to be included and type of approximations to be considered, depending on the specific application in hands.

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