Numerical simulation and Experimental characterization of RIFT process

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ABSTRACT

The resin infiltration during the RIFT process has been both simulated numerically by a finite element code and performed experimentally. In particular, the effect of a distributing media on the resin flow has been investigated analyzing the impregnation of glass fibers dry woven fabrics by an epoxy resin. Different experimental infiltration tests have been carried out by placing different layers of a distributing polymeric net media under the bag that has the function to ease the infiltration of the dry fibers. In all cases, the resin advancement as function of the time was measured and compared with the numerical results which were obtained by analyzing the flow along the planar surface and considering the distributing media as an additional layer with high permeability. Good agreement between the experimental and numerical data was found demonstrating the reliability and the capability of the developed model.

1. INTRODUCTION

The resin infusion processes are a group of promising and attractive low cost techniques that enable the manufacturing of high performance polymer based composite materials. The processing cycle involves the impregnation of a dry reinforcement by a thermoset resin. After complete infiltration, the resin reacts to form a cross-linked polymer network (cure reaction) giving the composite consolidation. In general, the process is known as Resin Transfer Molding when the resin is injected into a closed mold, while as Resin Infusion under flexible tool (RIFT) when the infiltration is driven by the vacuum and only one tool side is used being the other a polymeric flexible bag. Thus, the conventional RTM technique is a successful technology for small composite products in large series. On the other hand, the RIFT is interesting and more economical for the production of large size parts [1]..

Due to the complex nature of the process, the processing modeling and characterization coupled to a proper control should aid the design of the processing parameters and enable the manufacturing of high performance parts. For this reason, to optimize the processing cycle not only by trial and error procedures, some authors have developed numerical simulations able to model the resin infusion process [2-3]. Theoretically, accurate information about the processing evolution could be provided by modelling both the resin flow, the heat transfer, the chemo-rheological resin behaviour as in the case of RTM and compaction too [4].

In this study, the impregnation of glass fibers dry woven fabrics by an epoxy resin during the RIFT process has been simulated numerically and performed experimentally. In particular, the composite laminates have been manufactured by placing various layers of a distributing polymeric net media under the bag that is required to promote the infiltration of the dry fibers. Further, the resin advancement as function of the time was evaluated numerically by a finite element code where the distributing media was simulated as an additional layer with high permeability. A good agreement between the experimental and numerical data was found demonstrating the reliability and the capability of the developed model.

2. PHYSICAL MODEL

The resin flow during liquid molding processes is a typical moving boundary problem, characterized by a moving flow front that divides different phases: dry fibers and the wet fibers/resin system. In general, many authors have developed theoretical models of this kind of process all based on the Darcy's law [5- 7]. The most valid approach to describe the flow front advancement, being well adaptable to the numerical implementation of a moving boundary problem, seems to be the method proposed by Lin, which introduced a variable s, the degree of saturation, that represents the percent of void effectively occupied by the resin within a control volume. The s value is 0 in the dry fiber zone and 1 in the completely saturated zones. This variable has intermediate values just in proximity of the flow front. The adoption of the saturation degree allows the use of a fixed grid

In this work, the resin flow under isothermal conditions has been described by the Darcy law and introducing the degree of saturation**,** the percent of void effectively occupied by the resin within a control volume, as variable in order to account for the moving boundary nature of the problem. In this case, the mass conservation equation has the following form:

$$\phi \frac{\partial s}{\partial t} + \nabla \cdot \mathbf{q} = 0 \tag{1}$$

where ϕ is the reinforcement porosity, s is the degree of saturation and **q** the resin velocity. The substitution of the Darcy law relating linearly the resin velocity to the pressure gradient allows the calculation of the pressure field once proper boundary conditions have been set: fixed pressure at the injection gate, atmospheric pressure along the flow front, no slippage at the mold surface.
With this variable, combining the continuity equation with the Darcy's law, we obtain:

$$\phi \frac{\partial s}{\partial t} = \nabla \cdot \left(\frac{\mathbf{k}}{\mu} \cdot \nabla p \right) \tag{2}$$

where **k** is permeability tensor and p is the pressure.

3. NUMERICAL FORMULATION

The numerical simulations have been performed by using the saturation **s** of the FEM control volumes that offers significant advantages in terms of calculation time because it is not required to redraw the mesh at each time step. On the other hand, the position of the flow front is not exactly defined as it is located somewhere in the space between the nodes where saturation is 0 and the completely saturated nodes. Generally, the front can be placed in the nodes with saturation 0.5. Thus, the flow equation 2), discretized by the finite element method, have been solved by using a fixed mesh grid and an explicit time step scheme.
The application of the Galerkin's method to the equation (2), gives []:

$$[\mathbf{M}]\frac{d}{dt}[\mathbf{s}] + [\mathbf{K}][\mathbf{p}] = [\mathbf{f}] \tag{3}$$

$[\mathbf{M}]$ and $[\mathbf{K}]$ are respectively the mass matrix and the permeability matrix while $[\mathbf{f}]$ is the boundary conditions vector. The equation (3) has been simplified replacing the complete mass matrix with a diagonal matrix.
To solve the equation, an explicit time integration method has been used.
Matrix $[\mathbf{K}]$ can be considered as composed by three groups of equations, using subscript I to indicate the inlet nodes, subscript S to indicate the completely saturated nodes and U for the unsaturated ones. The following partition of equations (3) is obtained:

$$\Delta t \begin{bmatrix} \mathbf{K}_{\mathrm{II}} & \mathbf{K}_{\mathrm{IS}} & \mathbf{K}_{\mathrm{IU}} \\ \mathbf{K}_{\mathrm{SI}} & \mathbf{K}_{\mathrm{SS}} & \mathbf{K}_{\mathrm{SU}} \\ \mathbf{K}_{\mathrm{UI}} & \mathbf{K}_{\mathrm{US}} & \mathbf{K}_{\mathrm{UU}} \end{bmatrix}^t \begin{bmatrix} \mathbf{p}_{\mathrm{I}} \\ \mathbf{p}_{\mathrm{S}} \\ 0 \end{bmatrix}^t = \begin{bmatrix} \mathbf{M}_{\mathrm{II}} & 0 & 0 \\ 0 & \mathbf{M}_{\mathrm{SS}} & 0 \\ 0 & 0 & \mathbf{M}_{\mathrm{UU}} \end{bmatrix}^t \begin{bmatrix} 0 \\ 0 \\ \mathbf{s}^t - \mathbf{s}^{t+\Delta t} \end{bmatrix} + \Delta t \begin{bmatrix} \mathbf{f}_{\mathrm{I}} \\ 0 \\ 0 \end{bmatrix}^t \tag{4}$$

It is important to notice that matrixes $[\mathbf{M}]$ and $[\mathbf{K}]$ are not time dependent, while their partition changes as an unsaturated node becomes completely filled.
Solving the second row of the system, the pressure field in the saturated nodes is defined:

$$\{\mathbf{p}_{\mathrm{S}}\}^t = -[\mathbf{K}_{\mathrm{SS}}]^{t\,-1}[\mathbf{K}_{\mathrm{SI}}]^t\{\mathbf{p}_{\mathrm{I}}\}^t \tag{5}$$

From the third group of equations the explicit time step can be chosen as the largest time that doesn't change the matrix partition:

$$\Delta t_{\exp} = \min\left(\frac{M^{t}_{UUii} \cdot (s^{t}_{Ui} - 1)}{\sum_{j} (K^{t}_{UIij} p^{t}_{Ij} + K^{t}_{USij} p^{t}_{Sj})} \right) \tag{6}$$

Thus the saturation of each node can be updated by reintroducing the time step Δt_{exp} in the equation:

$$s^{t+\Delta t}_{Ui} = s^{t}_{Ui} - \Delta t_{explicit} \frac{\sum_{j} (K^{t}_{UIij} p^{t}_{Ij} + K^{t}_{USij} p^{t}_{Sj})}{M^{t}_{UUii}} \tag{7}$$

Finally, matrixes partition has to be changed and the new time step can be calculated.

4. EXPERIMENTAL

Rectangular composite laminates, based on glass fibers dry woven fabrics (600g/m^2) and an epoxy resin (I-SX10- Mates Spa) have been manufactured by RIFT process.
Figure 1 shows a schematic of the RIFT set-up.

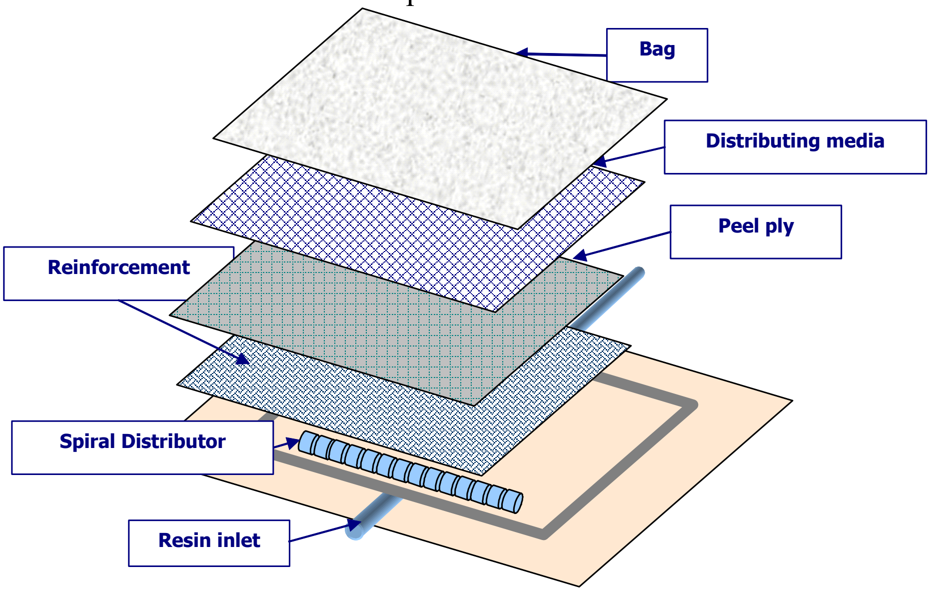

Figure 1. Schematic of the RIFT set-up.

Two pipes, connected respectively to the tank of the resin and to the vacuum pump, go into the resin-inlet and air-outlet points, that is located on opposite side of the mold.
The reinforcement layers, 20cm large and 30cm long, were placed on a transparent mould in plexiglass. A layer of peel-ply, three longitudinal distributor layers and a flexible PET bag were subsequently stacked on the reinforcement layers. Finally, the bag was sealed onto the mold.
The distributing media consists of layers of a polymeric net, generally as mosquito-net; a photograph of a net layer is shown in figure 2.
In addition, to uniform the flow front, another type of distributor, having a spiral shape and transverse to the flow, was placed before the inlet point.
Three kinds of composite laminates were produced using a different number of reinforcement layers respectively: 12, 18 and 24. The experimental measurement of the flow front advancement during the impregnation, three lines were considered on the below surface of the mold at a distance of 10, 20 and 30 cm from the inlet point. The lines were perpendicular to the flow direction. The time was measured as the flow front arrived at two points of each line. The two points divided in three equal part the line. Figure 3 shows a schematic of the control points position for the measurement of the impregnation time.

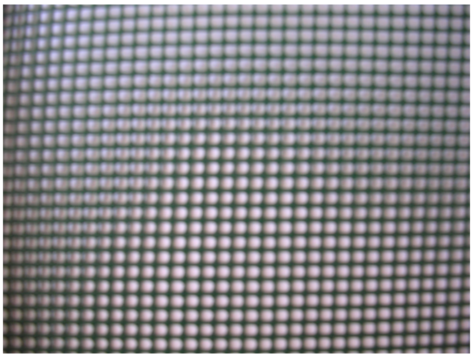

Figure 2. The polymeric net used as distributing media.

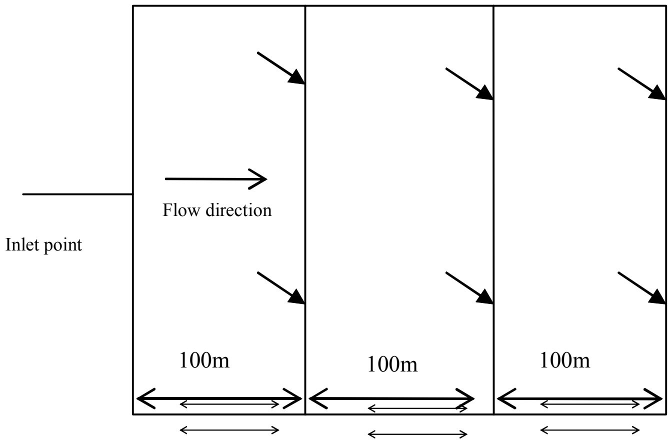

Figure 3. Position of the points to measure the infiltration time.

Table 1 reports the time values measured at every line for the different laminates.

Position (cm)	12 layers time (s)	18 layers time (s)	24 layers time (s)
10	30	35	35
15	60	65	70
20	84	94	100
30	140	156	170

Table 1. Impregnation time values.

In figure 4, the photograph of the impregnation stage is shown.

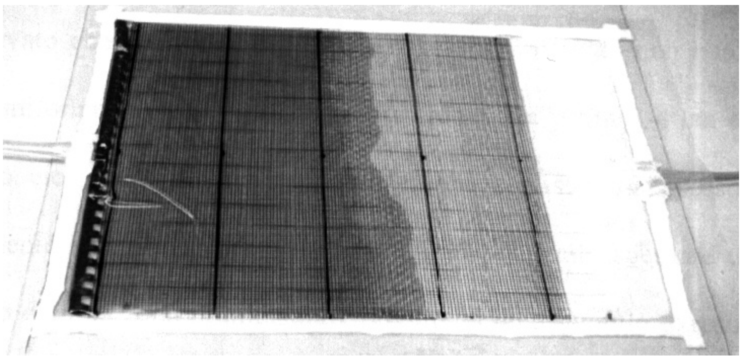

Figure 4. Composite Laminate manufacturing by resin infusion.

Permeability characterization

The permeability of both the reinforcement layers and the polymeric net was measured by performing other impregnation tests. In particular, the experimental tests have been carried out placing 4 layers of reinforcement followed by 2 layers of polymeric net between the mold and the bag. The layers were 15 cm large and 20 cm long. The volumetric flow was measured using a graduate tank and the permeability was calculated by Darcy's law.

From these tests, the volumetric flow resulted constant and equal to about 0,3 cm^3 per layer. This result was useful to calculate an apparent permeability for the polymeric net by adopting the hypothesis that the flow was 0,3 cm^3 for layer at the middle point of the laminate length (15cm).

Further, the transverse permeability was calculated by Darcy's law by measuring the volumetric flow with a graduate tank for the resin. A preform, constituted by 8 layers of reinforcement (dimension 10cmx10cm), was placed on the mold; a layer of peel ply, a layer of polymeric net and the flexible bag were stacked on the preform; successively the bag was sealed to the mold.

However, for this test, the inlet point was placed on the top surface of the distributor and the outlet point was placed on the mold as shown in figure 5.

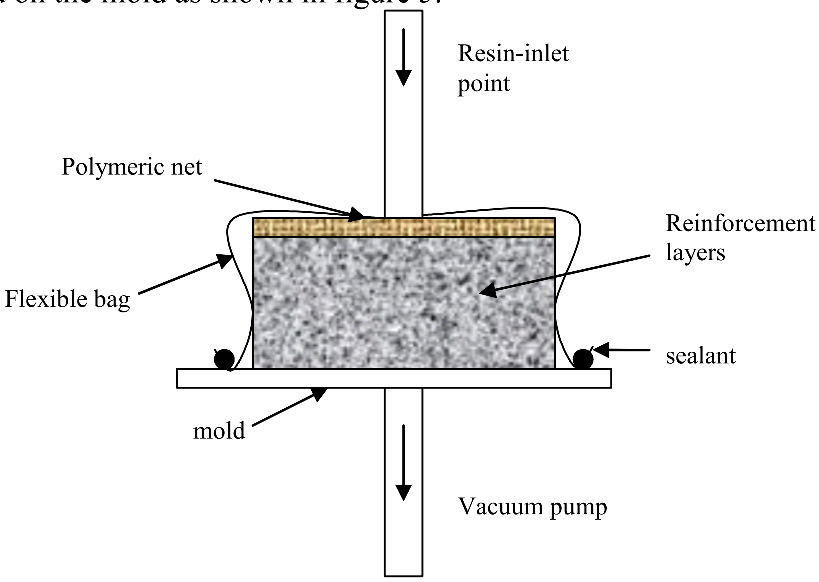

Figure 5. Scheme of the test to determine the transversal permeability of the reinforcement layers.

Table 2 summarizes measured values for the transverse and longitudinal permeability of both reinforcement and distributing net.

System	**Transverse Permeability, m^2**	**Longitudinal Permeability, m^2**
Reinforcement	$3 \cdot 10^{-13}$	$6 \cdot 10^{-10}$
Distributor	-	$4 \cdot 10^{-9}$

Table 2. Permeability of Mates reinforcement and of the distributor.

5. RESULTS

The RIFT manufacturing cycle of the composite laminates described above has bee simulated numerically, considering the distributing medium as additional reinforcement layers with high permeability (sse Table 2). The impregnation tests were performed at environmental constant temperature, hence the resin viscosity was constant and equal to 0.6 Pa·s. The resin flow was analysed along the flow parallel section.

Figure 6 shows the adopted rectangular mesh for the test 3. As one observes, the resin injection has been considered along the left side of the system, imposing atmospheric pressure at the injection and zero pressure along the flow front. In all cases, the same integration steps have been used along the two directions x and z, 0.003 and 0.0005 respectively changing just the node numbers along z.

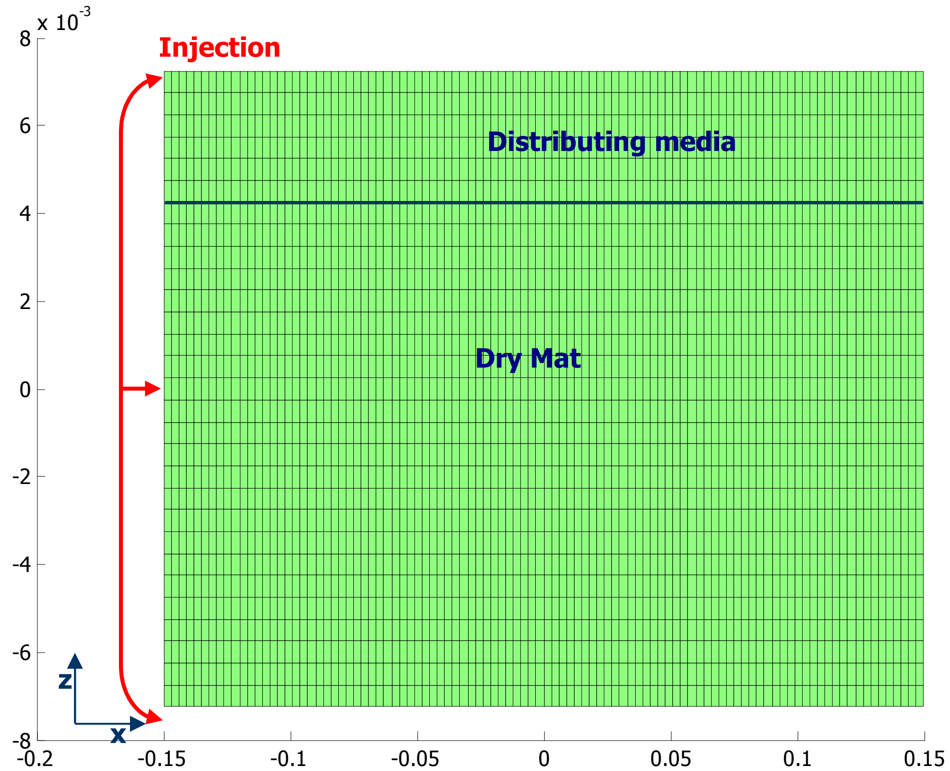

Figure 6. Adopted rectangular mesh for the numerical simulations.

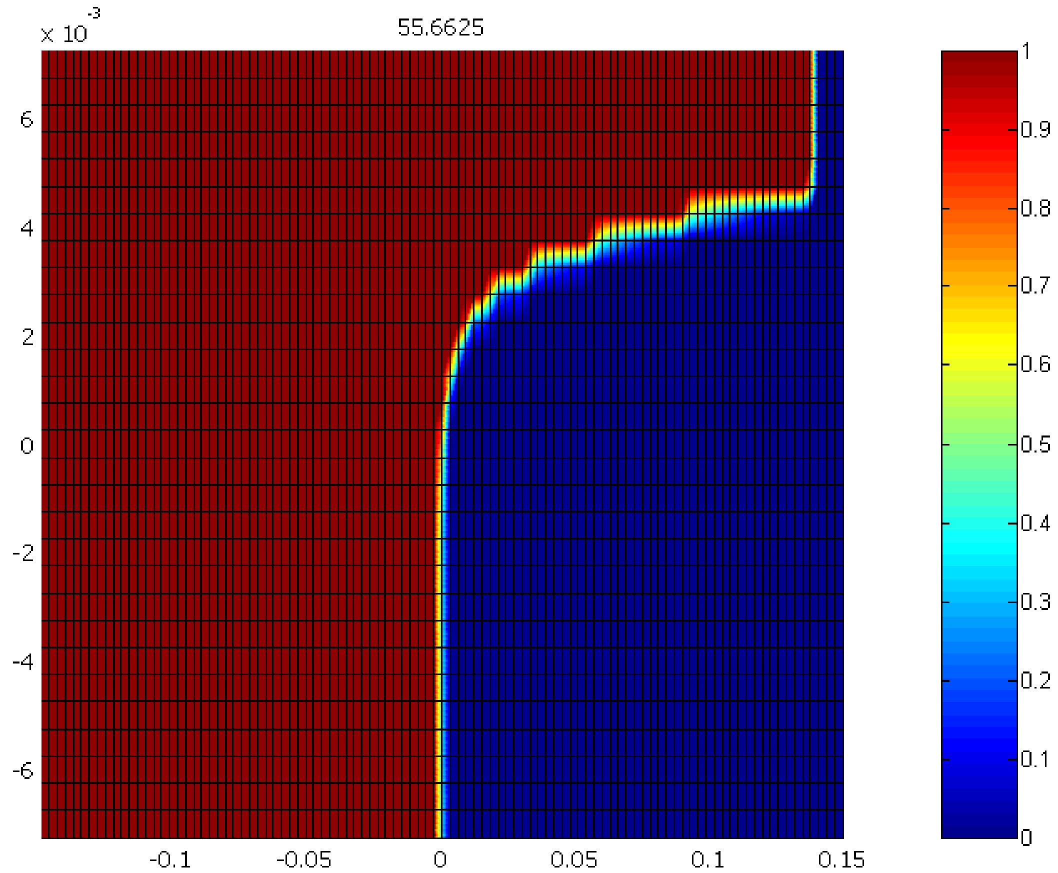

Figure 7. Resin advancement after 55.6 sec from the injection.

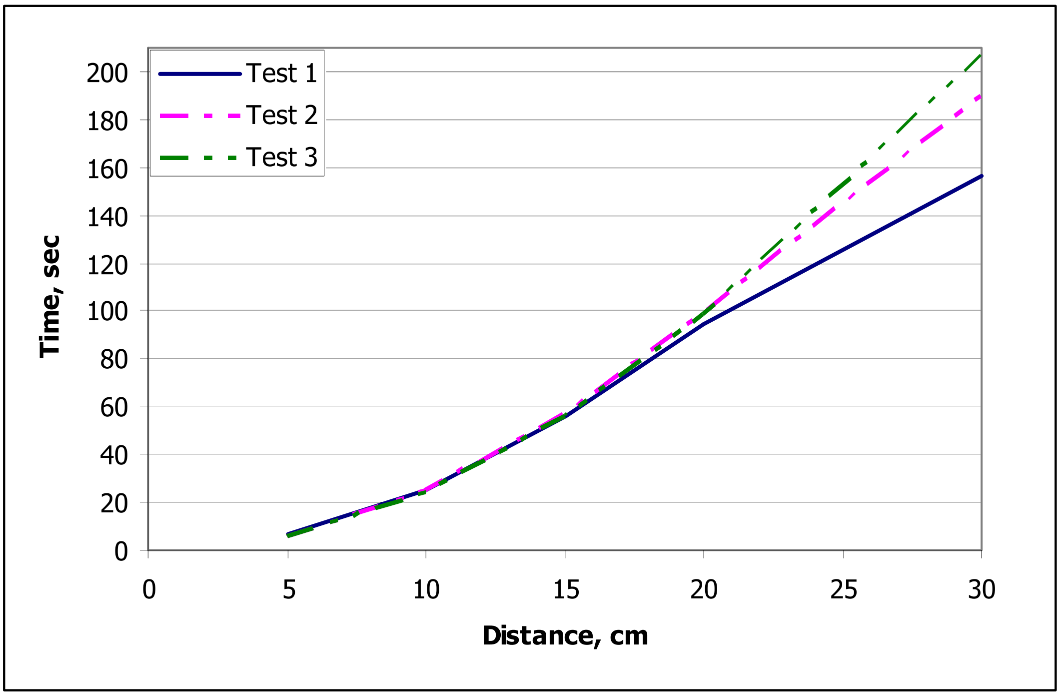

Figure 8. Infiltration time as function of the distance from the injection line for the three analyzed tests .

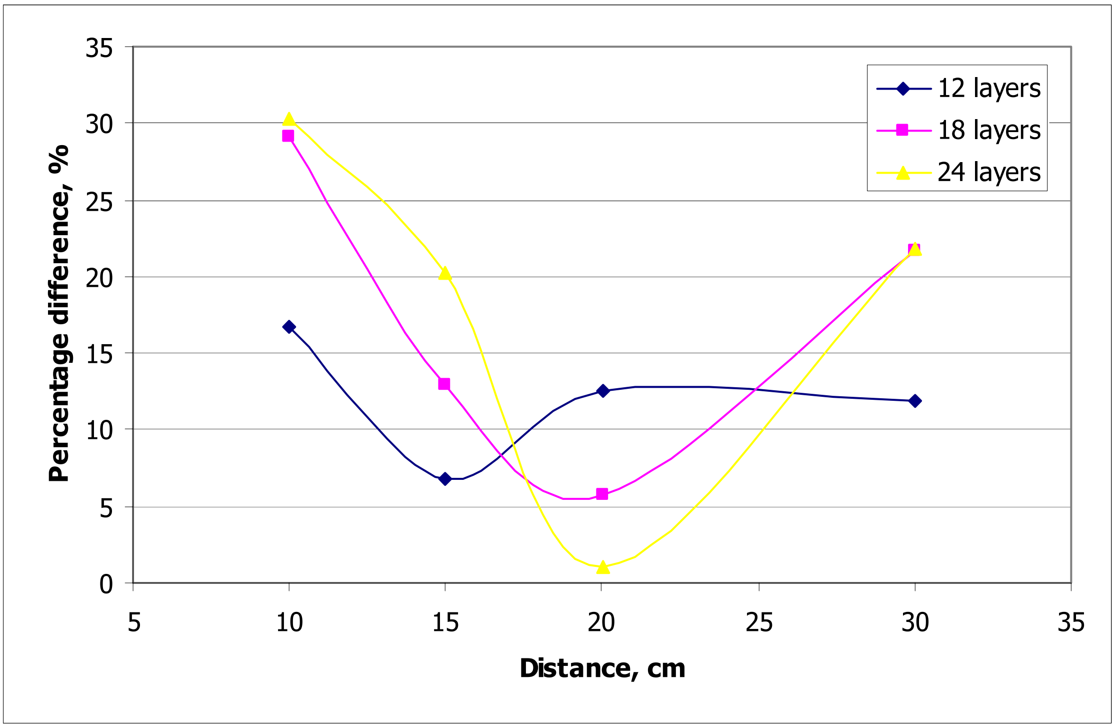

Figure 9. Percentage between the numerical and experimental infiltration time for the three analyzed tests .

Figure 7 shows the resin advancement map in the case of 24 glass fabric layers when the resin reaches half of the plate at 55.66 sec from the injection. The red zones are completely saturated by the resin, while in the blue zones the saturation degree is 0. One should observe that the distributing net is almost wetted by the resin. In fact, the resin initially fills the distributor and subsequently impregnates the fibers.

Figure 8 reports the numerical impregnation time as function of the distance from the injection gate for the three analyzed case. Obviously, the time required to completely infiltrate the fabric increases as the reinforcement layers increase. In addition, the differences between the three tests are more significant in the zone more far from the injection gate.

Finally, figure 9 shows the percentage difference between the experimental and numerical impregnation time as function of the distance from the injection gate for the three analyzed laminate configurations. In general, the differences are less than 30%. Further, the data find a more good agreement at the half of the mold. This result can be attributed both to the experimental difficulty to measure the impregnation time and the way used to evaluate the apparent permeability of the distributing net that was calculated by considering the volumetric flow rate at the middle point of the laminate length. Therefore, better results are expected in the first and final part of the mold if the flow rate measurements should be performed not only at the middle of the mold, but also in the other points. In this way, different apparent permeability values for the distributing net should be calculated and used in the various zones of the mold.

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