Simulating three-dimensional flow in compression resin transfer molding process

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ABSTRACT. Compression Resin Transfer Molding (CRTM) is a novel variation of traditional Resin Transfer Molding (RTM). It combines features of RTM, with those of traditional compression molding. The resin is introduced in the mold containing the preform in the narrow gap between the mold platen and the preform. As the resin flows in the narrow gap between mold and the preform, the mold platen squeezes the resin into the stationary preform, which also undergoes compression to create the desired fiber volume fraction. The flow field exhibits a three-dimensional character and is coupled with the fiber compression dynamics. We have modified our existing resin transfer mold filling simulation based on flow through porous media to model the resin injection in CRTM.

KEYWORDS: injection molding, resin infusion, fiber preforms, resin flow, flow modeling, fiber compaction, composites, numerical methods, process modeling.

1. Introduction

Liquid Composite Molding (LCM) processes have been increasingly explored as a viable option to manufacture composite parts. The process requires one to place a fibrous preform inside the mold. The mold is sealed and a liquid resin (typically a thermosetting resin, due to its low viscosity) is injected to saturate the preform. The fibers in the preform and the preform itself are stationary during the injection process. Next, the resin is allowed to cure. During the curing process, the resin cross-links and hardens. Once the resin had sufficiently solidified, the mold is opened and the part is removed. Two widespread techniques in this process are Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM), but there are several other processes of interest, such as RTM "Light" or Compression Resin Transfer Molding (CRTM). Figure 1 schematically compares these processes.

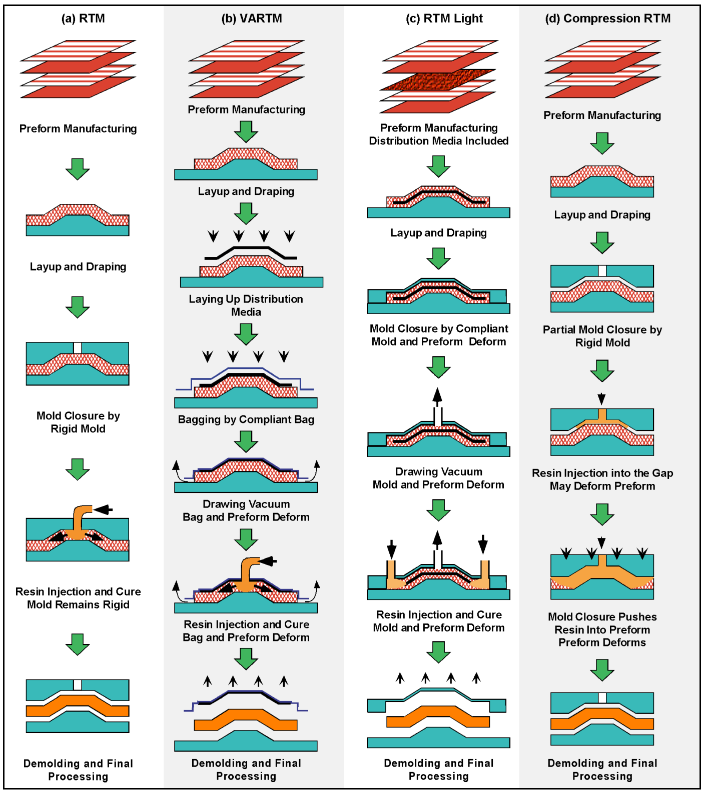

Figure 1. *Schematic comparison of several variations of LCM Processes: RTM, VARTM, RTM-Light and Compression RTM*

In all cases, the flow of the resin through the preform is very important. If gates and vents are not properly placed in the mold, particular sections of the preform may remain dry after the injection is complete, resulting in poor mechanical properties. It is usually difficult to intuitively guess the resin flow pattern for a variety of reasons. This created a need for the simulation of filling process using mathematical process model.

As far as the conventional RTM is concerned, many reliable computer simulation tools have been established and validated with experiments (Hieber *et al.*, 1980; Osswald *et al.*, 1988; Bruschke *et al.*, 1990; Lewis *et al.*, 1991; Voller *et al.*, 1995; Trochu *et al.*, 1993; Ngo *et al.*, 1998; Minaie *et al.*, 2002). They were used to verify designs and, more recently, for the purposes of process optimization and control (Mathur *et al.*, 1999; Lin *et al.*, 2000; Sozer *et al.*, 2000; Bickerton *et al.*, 2001; Kim *et al.*, 2002; Nielsen *et al.*, 2002). When the other LCM variations are involved, the modeling tools are scarce. Generally, RTM simulation has been used with mixed success for VARTM process, and the limits of validity for such an approach have being examined (Acheson *et al.*, 2004; Correia *et al.*, 2004).

Typical parts made by all LCM processes are shell-like structures. Hence, in most traditional RTM cases one can consider the flow of the resin through the fabric as two-dimensional and neglect the flow through the thickness of the part. The presence of distribution medium makes this assumption unsuitable in VARTM (or RTM Light) and in this work we will examine the significance of three-dimensional flow in compression resin transfer molding.

2. CRTM Process

Unlike the other common variations of LCM (RTM, VARTM, RTM Light – Figure 1 (a)-(c)), the resin flow compression molding process exhibits three distinct stages. These are shown in detail in Figure 2. All of the phases can be modeled as a flow through porous media under different boundary and initial conditions. The three stages can be divided into

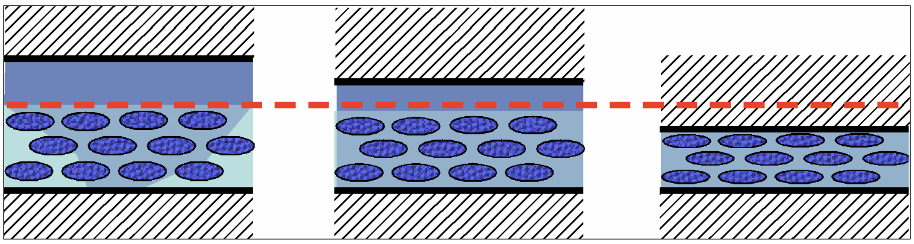

Figure 2. *Three phases of compression RTM (CRTM) process: (a) injection into the gap in mold, (b) closing the gap and (c) the final preform compaction*

1. Resin injection into the narrow gap between the mold platen and the fiber preform in the mold;

2. Closing of the gap without direct contact between tool and the preform;

3. Compaction of the preform by the mold platen along with resin impregnation.

Note that the first stage may overlap with the later ones and, depending on tool geometry and kinematics, a single composite structure may be undergoing different phases in different regions. We will, for the sake of simplicity, assume that these three stages follow linearly. This assumption may be readily released if necessary but at a cost of significant implementation complexity.

2.1. *Stage 1: resin injection into the narrow gap*

In the first stage, the resin is injected into the gap between the movable mold part and preform (Figure 2 (a)). It can readily spread through the gap, but it also slowly penetrates into the preform. This situation is similar to the flow in traditional VARTM with distribution media. In this case, the gap plays the role of distribution media.

The subtle question, to which we do not know the answer, arises from the pressure gradients applied through the preform thickness: does the preform undergo significantly compaction? However, one can assume that if the injection pressure is not extremely high, we may neglect this compaction.

2.2. *Stage 2: closing the gap*

In the second stage (Figure 2 (b)), the resin injection is switched off and the mold closure is initiated. The gap between the preform and the mold platen reduces as the mold closes and the resin is displaced and forced into the preform. The gap serves as a continuous source. However, if the resin did not fill the gap in stage 1, and this is a likely scenario, it will continue to preferentially flow into the gap during this stage as it encounters lower resistance as compared to impregnating the preform. As the gap thickness reduces, so does its resistance to the resin flow (permeability) and the flow behavior must account for this dynamic change in the permeability of the gap.

As in the previous phase, deformation of the preform through the pressure gradients is a possibility even though there is no mold-preform contact but for low pressure compression molding one could safely assume that this physical phenomena does not influence the flow in any significant way.

2.3. *Stage 3: preform compaction*

In the final stage (Figure 2 (c)), the gap between the preform and the mold platen is closed, and the mold wall is in contact with the preform and compresses the preform directly. Consequently, the resin is forced from already filled regions and the filled area also serves as a resin source to impregnate the unfilled regions in the mold. The preform compaction can be described reliably as the mold platen is in direct contact and its closing speed is usually known. Thus the volume fraction, permeability, etc. can be predicted at any time step during this stage. Notable exception to this rule is the case when the force required for compression is known, instead of the mold kinematics. If this is the case, the coupling between the mold closure and the pressure field will significantly complicate the modeling.

The advantage of CRTM, as related to more conventional RTM processes is that it combines the net-shape high-performance part with the fast cycle time compatible with rapid manufacturing process a requirement for large volume production industries such as automotive industry. Significant process and geometric complexity mandates the use of reliable predictive modeling so that one can find the optimal processing time and minimize manufacturing defects.

3. Process model

All three stages of the CRTM process described above are similar to other RTM variations as they represent a pressure driven flow in porous medium. In this section, we will first examine the traditional RTM modeling approach. Next, the differences introduced by the CRTM specific features will be stated and changes necessary in the simulation will be put forth to successfully model the CRTM injection phase.

3.1. *Traditional RTM modeling*

The resin flow into a thin closed mold cavity can be represented as flow through porous media, usually with negligible inertial effects due to the high viscosity of the resin (Tucker *et al.*, 1994). To describe the physics of such a flow one usually uses Darcy's law and the continuity equation to formulate the governing equation. Darcy's law can be expressed as

$$\langle \mathbf{v} \rangle = -\frac{\mathbf{K}}{\eta} \cdot \nabla p \qquad [1]$$

Here $\langle \mathbf{v} \rangle$ is the volume averaged flow velocity, ∇p is the pressure gradient in the impregnating fluid, η is the viscosity of the fluid and second order symmetric and positively definite tensor $\mathbf{K}$ describes the permeability of the fibrous porous media. If the mold is non-deformable and both the resin and preform (fiber) material are incompressible, the continuity equation can be written as

$$\nabla \cdot \langle \mathbf{v} \rangle = 0 \quad [2]$$

Substitution of equation [1] in the continuity equation [2], results in the following governing equation:

$$\nabla \cdot \left(\frac{\mathbf{K}}{\eta} \cdot \nabla p \right) = 0 \quad [3]$$

This equation is usually solved to provide the pressure field for a given configuration. Flow velocity is then computed from equation [1] to provide description of the flow.

Modeling flow of the viscous liquid into the mold involves a moving boundary. There are several ways to numerically simulate the filling process (Hieber *et al.*, 1980; Osswald *et al.*, 1988; Bruschke *et al.*, 1990; Lewis *et al.*, 1991; Voller *et al.*, 1995; Trochu *et al.*, 1993; Ngo *et al.*, 1998; Minaie *et al.*, 2002), mostly based on the quasi-steady approach. The finite element/control volume (FE/CV) solution scheme to simulate the filling process has served well to capture this physics efficiently (Bruschke *et al.*, 1990).

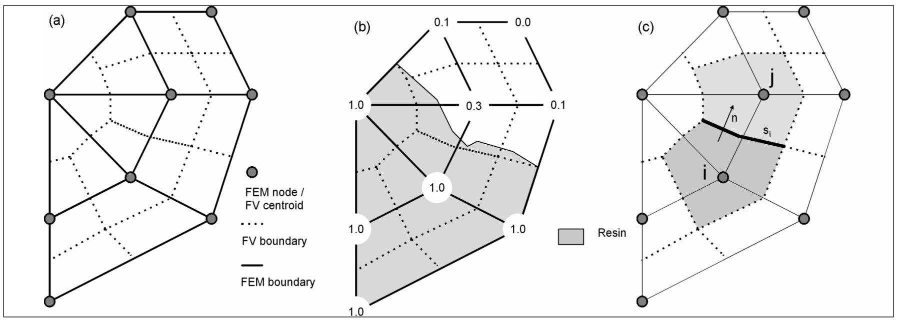

Figure 3. *Finite Element/Control Volume numerical model for filling of porous media: (a) Domain discretization into finite elements (pressure computation) and control volumes (flow computation), (b) Fill factors associated with control volumes and (c) Flow between the control volumes*

The solution domain is meshed with a fixed finite element mesh. Control volumes are associated with each mesh node or alternatively every element (Figure 3 (a)). Each control volume has a fill factor associated with it. This factor ranges between zero (empty CV) and one (filled CV) and indicates the fraction of the available volume already filled with the fluid (Figure 3 (b)). The pressure in the empty control volumes is known to be equal to that of the vent and the pressure in the filled control volumes is evaluated by the finite element method, using [3]. Then, the flow Q_{ij} between individual control volumes i and j is determined using the computed pressure field (Figure 3 (c)).

$$Q_{ij} = \int_{s_{ij}} n_i . \frac{\mathbf{K}}{\eta} \cdot \nabla p ds_{ij} \qquad [4]$$

Once the flow rates are known, flow is advanced by explicit integration in time domain. The time step is selected so as to fill at least one additional control volume. This changes the fluid domain and hence the boundary conditions. The pressure solution is sought for the new domain. This process is repeated until the complete mold is filled.

This approach is relatively mature and widespread (Bruschke *et al.*, 1990; Lewis *et al.*, 1991; Voller *et al.*, 1995; Ngo *et al.*, 1998), fairly simple and quite robust, and its utilization stretches into the fields of optimization and control (Mathur *et al.*, 1999; Lin *et al.*, 2000; Sozer *et al.*, 2000; Bickerton *et al.*, 2001; Kim *et al.*, 2002; Nielsen *et al.*, 2002). More importantly, if "incremental" system matrix decomposition is used (Maier *et al.*,1996), the solution is very fast, as the set of system equations is solved only once for the complete filling cycle. The efficiency comes with some restrictions. The incremental algorithm requires the system matrix not to change during the process, which necessarily means that the process must remain linear. Also, being a direct solver (with inevitably sub-optimal matrix bandwidth), memory requirements of its implementation can be very high for large problems. If any of these difficulties are encountered there are other efficient solution techniques available (Hieber *et al*., 1980; Trochu *et al*., 1993).

3.2. *Challenge of deformable preform: changes in governing equations*

The conservation of mass, equation [2] assumes that the porous medium does not deform. Once the control volume associated with the porous medium starts changing during the flow, new source term appears in equation [2]. For small deformation one can use infinitesimal volumetric strain rate $\dot{\varepsilon}$ and a coordinate system fixed to the porous media. Then, one can write the mass conservation as follows:

$$\nabla . \langle \mathbf{v} \rangle = -\dot{\varepsilon} \qquad [5]$$

The use of infinitesimal strain limits the acceptable deformation. Moreover, evaluation of deformation field would require known stress-strain relation in fibrous preform and evaluation of stress field. This is a formidable task however one can make several reasonable assumptions to simplify the solution without losing the important physics as stated below:

1. The preform deforms through-the thickness only. This assumption is true for most variations of LCM preforms that undergo deformations;

2. The preform deforms uniformly through the thickness. This assumption relies on identical or at least similar material used in all layers of the preform. Thus, there are cases in which it will not be valid though it is acceptable in most applications;

3. The preform deformation is "reasonably" small, to make linear strain acceptable. This will, again hold in most cases though exemptions exist when preform is very compliant, such as in the cases with inter-laminar distribution media. Note that it is quite simple to extend the method described here to allow for larger deformations.

With these assumptions, we can replace the strain rate by the rate of change of preform thickness $h(\mathbf{x},t)$ as follows:

$$\nabla.\langle \mathbf{v} \rangle = -\frac{\dot{h}(\mathbf{x},t)}{h_0(\mathbf{x})} \qquad [6]$$

where h_0 is the original preform thickness, before the mold starts compressing it. Utilizing Darcy's law (equation [1]) we can obtain the governing elliptic PDE for pressure as follows:

$$\nabla.\left\langle \frac{\mathbf{K}(h)}{\eta} \cdot \nabla p \right\rangle = \frac{\dot{h}(\mathbf{x},t)}{h_0(\mathbf{x})} \qquad [7]$$

This equation looks similar to those for compressible preforms derived elsewhere (Acheson *et al.*, 2004; Correia *et al.*, 2004), but it differs in a *very* significant way: The thickness variation is known as a function of time (and location) from the kinematics of the tooling. This means that neither the source term on the right hand side, nor the permeability value **K** on the right hand side is coupled with the unknown pressure field. The pressure field is related only to the fluid pressure averaged over the pores. Thus, we still have a linear PDE for pressure, albeit with transient coefficients and a forcing term. On the other hand, the compressive force cannot be evaluated unless additional constitutive model is introduced for preform stress-strain relations.

The usual, quasi-static solution of the problem ([3]) may be modified for equation [7] by following the steps below:

1. At a particular time step, filled region represents the solution domain. Permeability and the rate of deformation are known and the equation is solved to determine the primary variable, which is the pressure. Flow rates are determined using Darcy law once the pressure is known at the nodes and flow is advanced accordingly by explicit time integration over a selected time step to include more filled control volumes in the solution domain.

2. Thickness is changed accordingly and new permeability values are computed.

Assuming that the pressure approximation is constructed using a standard finite element scheme as:

$$p = \sum_i p_i . N_i(\mathbf{x}) \quad [8]$$

we can discretize the pressure equation [7] using the standard FEM scheme to obtain:

$$S_{ij} . p_j = Q_i \quad [9]$$

where

$$S_{ij} = \frac{1}{\eta} \iiint_V \nabla N_i \cdot \mathbf{K(x)} \cdot \nabla N_j dV \quad [10]$$

and

$$Q_i = \iiint_V N_i(\mathbf{x}) \frac{-\dot{h}(\mathbf{x})}{h_0(\mathbf{x})} dV \quad [11]$$

As stated above, the source term, Q_I, is independent of the unknown pressure p. Equation [9] is fundamentally the same as if we created a constant flow-rate inlet at every node (and its associated control volume). The inlet's magnitude corresponds to the rate at which the control volume is being compressed. The integration will, of course, distribute the flow rate according to FEM approximation, not according to the control volume method, but the difference should be negligible. The two will be identical for linear elements of constant thickness.

3.3. *Permeability and deformation*

Besides creating the "source" effect, preform deformation also changes the preform properties necessary to compute pressure field and flow, most importantly the permeability and porosity (fiber volume fraction).

One usually studies the relation between preform permeability and its fiber volume fraction or porosity. To relate the fiber volume fraction to deformation is, however, a trivial task, assuming that our assumption is valid. As the fibers are essentially incompressible, one can equate the reinforcement volume before (subscript *0*) and after deformation takes place and write:

$$v_{f0}.1 = v_f.(1-\varepsilon) \qquad [12]$$

where ε is the bulk strain describing the preform deformation. Consequently, we obtain:

$$v_f = \frac{v_{f0}}{1-\varepsilon} \qquad [13]$$

Note that we use the strain value and not the strain rate in this equation.

The dependence of permeability on the fiber volume fraction $\mathbf{K}(v_f)$ has been studied for various cases, but there seems to be no generally accepted, physically meaningful formula. Karman-Kozeny equation

$$\mathbf{K}(v_f) = \mathbf{k}\frac{(1-v_f)^3}{v_f^2} \qquad [14]$$

is commonly being used for this purpose, often as a curve-fitting tool, because of its simplicity. The results are usually acceptable, though it may be possible to achieve better fit using other formulas in individual cases (Bruschke *et al.*, 1993). In our case, all we need is a generic relation between v_f and **K** in order to set the parameters in equation [7] properly. We will label it as

$$\mathbf{K}(v_f) = \mathbf{f}(v_f) \qquad [15]$$

Here ***f*** could be a tensor function. For usual fibrous preforms, it is likely that the relations for in-plane and through-the-thickness components may be different.

3.4. *Modeling with RTM governing equation*

Sensible approach to the solution of equation [7] would require one to undertake several steps:

1. Code should be modified to evaluate and track the local deformation and to update volume fractions and permeability (equations [13] and [14]) internally;

2. The equation [7] should be used to assemble the system of equations and forcing term [9]-[11] in each solution step:

3. Solver different than the Maier's incremental decomposition (Maier *et al.*, 1996) should be implemented, because the mentioned algorithm degenerates into a direct Crout matrix inversion with *possibly* very sub-optimal bandwidth if the stiffness matrix changes at each time step.

While this solution is desirable and quite feasible, it is possible to simulate compression RTM filling using the existing RTM simulation code. It is only necessary that the preform properties and inlet parameters may be changed during the simulation execution and that there be no limit for the number of inlets. It is not even necessary for the simulation code to do the modifications internally. Thus, the CRTM filling simulation using RTM governing equations and simulation steps would be as follows:

1. Simulate the injection into the open gap as usual up to the point when the gap starts closing;

2. Save the simulation state;

3. Modify the volume fraction and permeability values. Then, create the constant flow inlets in all filled control volumes that are being compressed (as shown by equation [11]). Note that as long if the mold is not in the contact with the preform, only the gap gets compressed (phase 2);

4. Reload the data into the simulation and re-run the simulation for the next time step;

5. Save the results and, if the mold is not filled, return to step 3.

Our simulation does have the capability to evaluate the property within the simulation (point 3) due to the scripting capability which makes it seamless for us to adopt the RTM simulation to address CRTM.

4. Implementation issues

4.1. *Geometry model*

Composite structures are usually thin shell-like structures, which suggests two-dimensional filling simulation will suffice to capture the flow physics. This is true if the velocity through the thickness is uniform and this will be the case if the permeability through the thickness is one homogeneous value. However, if there is an open channel on top of the preform, one needs to consider the three-dimensional flow effects, as confirmed from analysis conducted with VARTM because the flow in the open channel has a much higher permeability as compared to the preform permeability through the thickness. We assume that the coordinate system axes x, y are aligned with the plane of the flat preform and the axis z is along the direction of its normal (Figure 4). The thickness of gap will be *h*, the thickness of preform is labeled as h_{pref}. For non-flat surfaces, it would be necessary to introduce the local coordinates, but the technical details on how to establish these directions, especially using only the mesh data are beyond the scope of this paper.

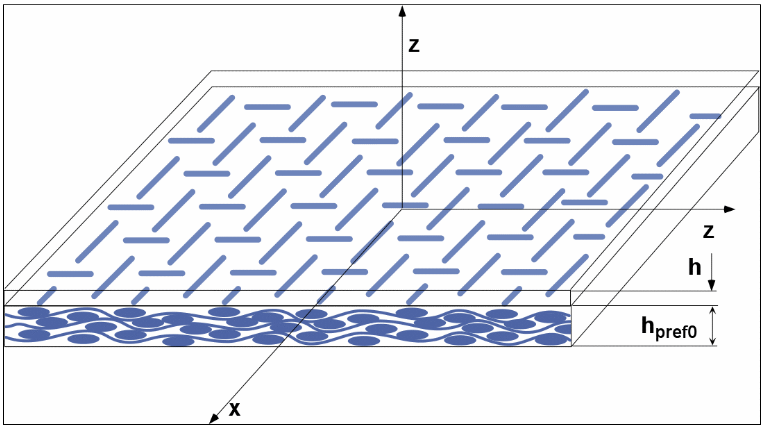

Figure 4. *Coordinate system, preform orientation and dimensions as used in the process model for CRTM*

We decided to model the preform as a three-dimensional porous solid with fixed dimensions. This will correspond to either the original preform or to the compacted final part, but one has to be careful to set the volume fractions and permeability according to the selected reference state. Note that the preform is being compressed only in the third phase of the process, *i.e.*, any deformation caused by resin pressure in previous phases is neglected. The permeability and volume fraction are modified accordingly.

The channel on top is modeled similarly as a standard distribution medium in VARTM, using two-dimensional elements (Modi *et al.*, 2002) as shown in Figure 5. Unlike stress analysis, the discretized form of Equation [3] allows such modeling provided rules of element connectivity are observed.

There are two reasons for adopting such a non-homogenous model when thin gaps and highly permeable regions are present in the porous media. First, through-the-thickness ("transverse") permeability of the thin gap or layer of porous material is difficult to establish. Second, aspect ratio of three-dimensional elements representing the gap ushers in a host of numerical difficulties related to element aspect ratio. The above mentioned approach solves both issues by constraining the flow in the gap or the highly permeable distribution media to be two dimensional, which is a justifiable assumption.

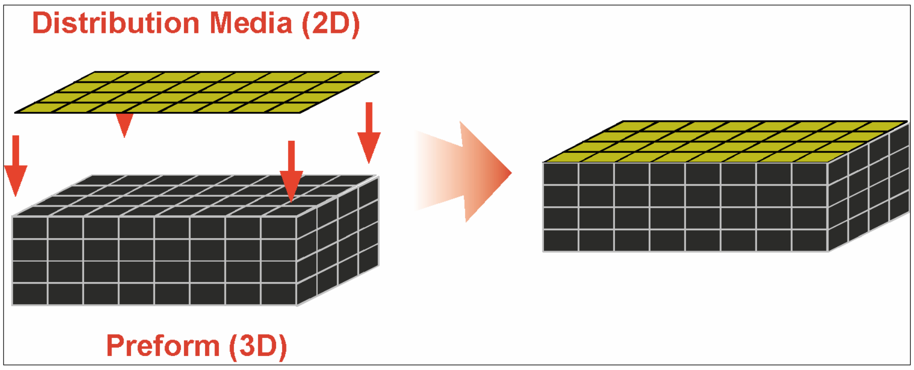

Figure 5. *Model for VARTM distribution media made of two-dimensional model of distribution media and three-dimensional model of preform*

The only change relative to the way this model is used in VARTM for distribution media is that the equivalent permeability of the gap is approximated from the equations for creeping (lubrication) flow in narrow channel of given height (thickness) as

$$K_{xx} = K_{yy} = \frac{h^2}{12} \qquad [16]$$

This is obviously acceptable only if the thickness of the gap *h* is much smaller than the in-plane dimensions of the part.

The thickness *h* is constant in the first stage, and then it continuously varies during the stage 2 from the original value to zero. The permeability must be modified accordingly. In the last phase the gap is non-existent, which can be accomplished by setting its thickness and permeability to zero.

Note that it would be possible to create even more complex model that accounts for the neglected preform deformation during the stages 1 and 2. There is little reliable experimental data and no accepted constitutive model for this deformation, therefore its introduction would not necessarily improve the accuracy of the model.

The mold is assumed to be rigid and its motion is described by the vector of its velocity ***v***, with the displacement ***x****(t)*. These values are known throughout the process.

We will label the time when the first and the second stage end as *t1* and *t2* respectively.

4.2. *Modeling algorithm: stage 1*

In the first stage, the mold is fixed. Resin is injected into the channel on top of the preform and is simulated as ordinary VARTM injection with distribution medium of thickness *h*, fiber volume fraction of 0 and permeability as described by Equation [16].

The simulation at this stage can predict the time required for injection of required volume of resin, which is known as the final part dimensions and fiber volume fraction are known in advance. This is trivial if the simulation uses flow-rate control, but the simulation provides the flow rates at inlet(s) in any case. These can be integrated to provide the volume of resin injected during a certain time period as shown - for a simple rectangular plate - in Figure 6. This time-volume relation is usually non-trivial to predict in complex cases but for this case the closed form solution for radial flow might be acceptable approximation, though it does not account for the porous media on one side of the gap.

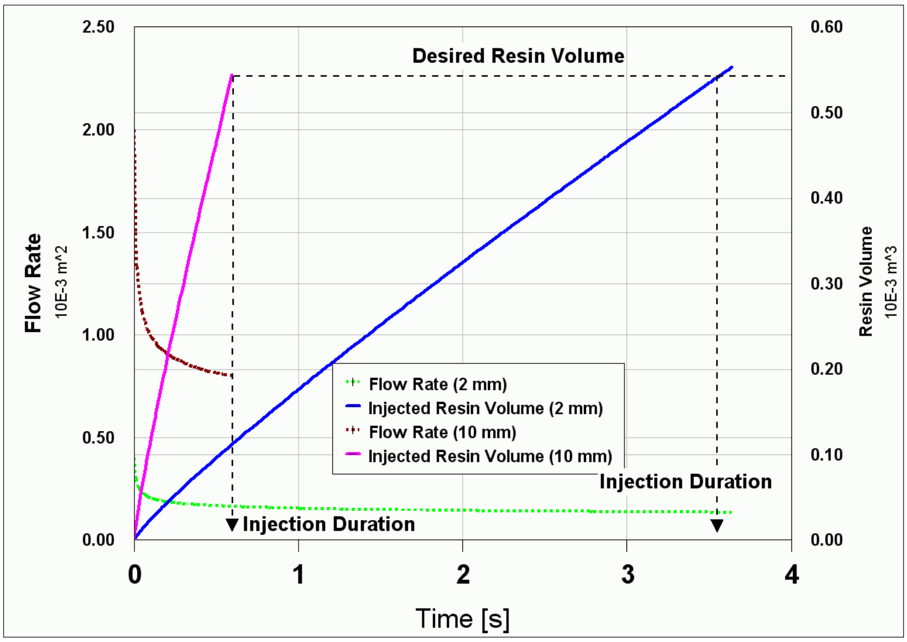

Figure 6. *Flow rate at injection gate and total volume of injected resin (two different sizes of gap). Simple establishing of injection time from simulation results*

The injected volume will depend on several parameters. The gap size dependence is illustrated in Figure 6, which shows the injection into a plate with two different gap sizes. The ratio of preform transverse permeability and square of gap thickness h^2 will be the second important parameter, as it determines how much the permeable wall of the gap influence the flow.

The only assumption made at this stage is that the preform itself does not deform as the pressure continues to build. Since the resin pressure will cause some deformation, this may reduce the modeling accuracy by a certain degree, though the pressure build-up in the gap is likely to be limited. To estimate this error one would need to obtain reliable compaction data (dry *and* wet) for the preform. If this data is available, the assumption can be eliminated. However it will reduce the computational efficiency and is not clear if we will gain much in terms of the physics by the inclusion of the compaction.

4.3. *Modeling algorithm: stage 2*

In this stage the upper mold platen moves with speed ***v***, while there is no resin injection into the mold and the injection gate is closed. The thickness of the gap changes as:

$$\frac{\partial h}{\partial t} = \dot{h} = \mathbf{v} \cdot \mathbf{n} \qquad [17]$$

where ***n*** is the normal vector to the part surface. Every saturated node *i* in channel represents a control volume with certain area A_i. The change of thickness in this area h_i results in resin source Q_i that is applied at that node as follows:

$$Q_i = -A_i \dot{h}_i = -A_i \left(\mathbf{v} \cdot \mathbf{n}_i \right) \qquad [18]$$

where $\boldsymbol{n}_i$ is the local normal to the part surface. This value might change with each step. Even if the mold speed is constant, one still has to set new “inlets” in newly filled control volumes with every time step. One also has to obtain the new thickness before each step and update the permeability in the channel whose gap is reducing due to the closure of the mold platen:

$$\begin{aligned} h &= h_0 - \int_{t1}^{t} -\mathbf{v.n}\, dt \\ K_{xx} &= K_{yy} = f(h) \end{aligned} \qquad [19]$$

This is updated for each element. The process is straightforward but care is needed to prevent generating elements with negative thickness of the channel due to the round-off error.

Note that since the process varies the permeability, fiber volume fraction and thickness of elements in regions of the geometry, the incremental matrix inversion algorithm of Maier (Maier *et al.*, 1996) as implemented in our code (Simacek *et al.*, 2004) is no longer advantageous. The computational performance could be significantly improved by applying a different, preferably iterative, algorithm.

As above, the only assumption is made that the preform itself does not deform as the pressure builds-up. One could eliminate this error if we had the compaction data by following these steps; (i) Compute the through-the thickness deformation at each location (ii) Adjust the dimensions of the gap accordingly (iii) Adjust the properties of preform and (iv) create flow source in filled preform that is being compressed. The last two points are examined below in Stage 3.

Additionally, we neglected the partially filled volumes. The fill factor of these volumes should be updated as they get compressed and, if it reaches unity, flow source should be introduced for that element. This results in net loss of resin volume during the simulation. This simplification may be alleviated at a cost of implementation complications. Note that the accuracy is also affected by the explicit time integration over finite time steps, though this error should go to zero with infinite refinement of the mesh.

4.4. *Modeling algorithm: stage 3*

In this phase, the physics is (i) There is no resin being injected and (ii) The gap is non-existent. The resin source is the preform itself that is being deformed by compaction. Using a three-dimensional solid, we cannot easily change the "thickness". However, we can modify its properties to reflect the correct porosity and permeability:

$$
\begin{aligned}
h_{pref} &= h_{pref\,0} - \int_{t2}^{t} -\mathbf{v}\cdot\mathbf{n}\,dt \\
v_f &= v_{f\,0}\cdot\frac{h_{pref\,0}}{h_{pref}} \\
\mathbf{K} &= \mathbf{f}\left(v_f\right)
\end{aligned}
\qquad [20]
$$

In equation [19] we used unloaded preform thickness and volume fraction (h_{pref0} and v_{f0}) as reference values to evaluate preform thickness and volume fraction (h_{pref} and v_f). Note that the in-plane permeability **K** components are "fictitious" because flow is computed from the original preform dimensions. Thus, the **K** contains not only the permeability change ([14]) but also lumps the thickness change effect on flow.

The preform thickness and the normal (through-the-thickness) direction **n** is not immediately obvious in three-dimensional meshes and one needs to perform substantial book-keeping to determine these values and to track them.

Then, we need to create the flow-rate gates in every filled control volume of the domain. For this purpose we need to calculate the original control volume, V_{i0}, as well as the original thickness h_{i0} to obtain the "area". Then, we can set the flow rate to be

$$Q_i = -\frac{V_{i0}}{h_{i0}}(\mathbf{v} \cdot \mathbf{n}) \qquad [21]$$

In each time step, the closing speed **v** may change and one must set new inlets in the volume(s) just filled and modify the ones filled previously. As above, the incremental matrix inversion is not possible and use of a solver based on this algorithm causes the solution to be quite slow and is memory-intensive.

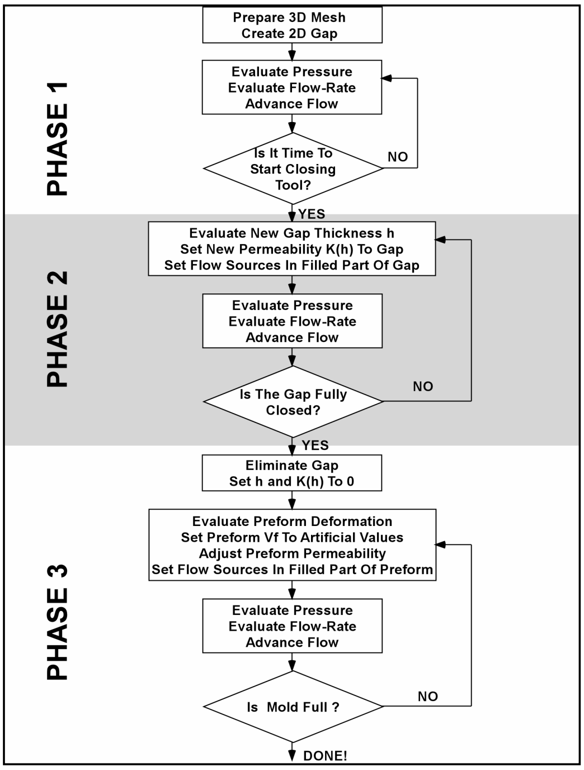

Figure 7. *Flow-chart of CRTM modeling using the described approach. The integration in time is explicit in all three phases*

The evaluation of [21] should be carried out on "per control volume" basis for each node in the mesh. However, the value is "averaged" through the thickness, assuming that the deformation is uniform through the thickness. This assumption is reasonable if, and only if, the preform is saturated through the thickness, *i.e.*, for very thin flat parts. Otherwise, through-the thickness pressure and saturation gradients will cause variations in deformation and deformation rates. However, to alleviate this problem one would need to solve coupled elasto-visco-plastic deformation problem in the three-dimensional preform.

Also, the change of fill-factors in partially saturated volumes in preform was not accounted during the updates of material and geometry updates as in the previous stage. This introduces small inaccuracy in the mass conservation of resin.

The entire modeling approach is summarized in the flowchart present in Figure 7.

5. Example

As an example and proof-of-concept, we will examine a simple case of injection into a plate (Figure 8). The original injection location is at the center of the plate, the injection parameters and material data are given in Table 1. The original thickness of the preform is h_{pref0} and its original volume fraction v_{f0}. The target volume fraction is v_f.

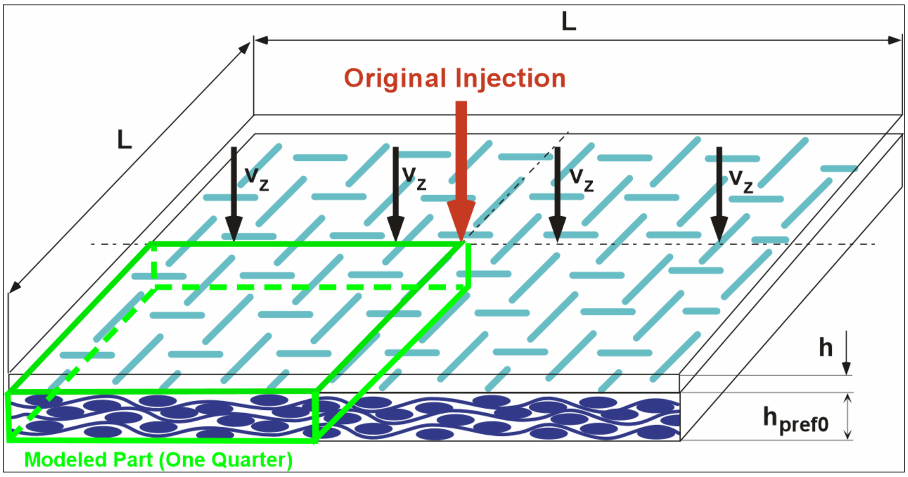

Figure 8. *CRTM injection into a rectangular plate. Model geometry, kinematics and process parameters are given in Table 1*

Table I. *Material data for the example in Figure 8*

Quantity	Value	Unit
L	1.00	Meters (m)
h_{pref0}	0.01	Meters (m)
v_f	0.45	dimensionless
v_{f0}	0.35	dimensionless
K_{xx}=K_{yy}	1.10^{-11}	m^2
K_{zz}	1.10^{-12}	m^2
h	0.005	m
v_z	1.10^{-5}	m/s
$p_{inj}t_1$	100,000300	Pas
ηp_{inj}	1100,000	Pa.sPa
η	1	Pa.s

Note that we will utilize the obvious symmetry and model only one quarter of the part as shown in Figure 8. Thus, for the following example the injection location is placed in the right corner.

The necessary time of injection is evaluated during the simulation; when there is sufficient resin injected, the inlet is closed and the compression starts. Similarly, phase 3 begins when the gap is closed and the exact time is determined during the simulation run. Essentially, the simulation algorithm is coded in a script, which takes care of all these details and the user is responsible only for the input parameters

The resulting flow-fronts are shown in Figure 9. Obviously, at inception the flow is very similar to radial flow. Once sufficient resin is injected for the required fiber volume fraction, the injection is discontinued. In phase 2, as the compression begins, the flow at first continues to fill the gap in radial fashion and then saturates the preform, almost fully in the through-the-thickness direction.

Simulation monitors the flow-rate at the gate. The data is shown in Figure 10, in logarithmic scale to cover the complete range of the process (compared to Figure 6 which shows only phase 1). Note the steps indicating the flow-rate during the phase 2 (compression of the gap) and phase 3 (compression of the preform). This flow-rate should be negative, as the resin is escaping the control volumes around the gate, but the source value that we set has to reverse the sign (the volume of already filled control volumes is no longer monitored).

The simulation, which was implemented based on RTM package LIMS (Simacek *et al.*, 2004) using its scripting capability worked reasonably well, with script taking care of all the details. There are, however, two issues that should be mentioned:

– The computational intensity increases by an order of magnitude when compared to the traditional RTM simulation. This is because the incremental decomposition of system matrix does not work if material parameters are changed during the injection and full decomposition is forced with every step. This can be alleviated only to a limited degree by choosing a different solver;

– The global volume conservation is not very good, with errors on level of over 10%. This seems to be caused by the unaccounted resin in the partially filled control volumes and the time domain integration and will be examined in detail later.

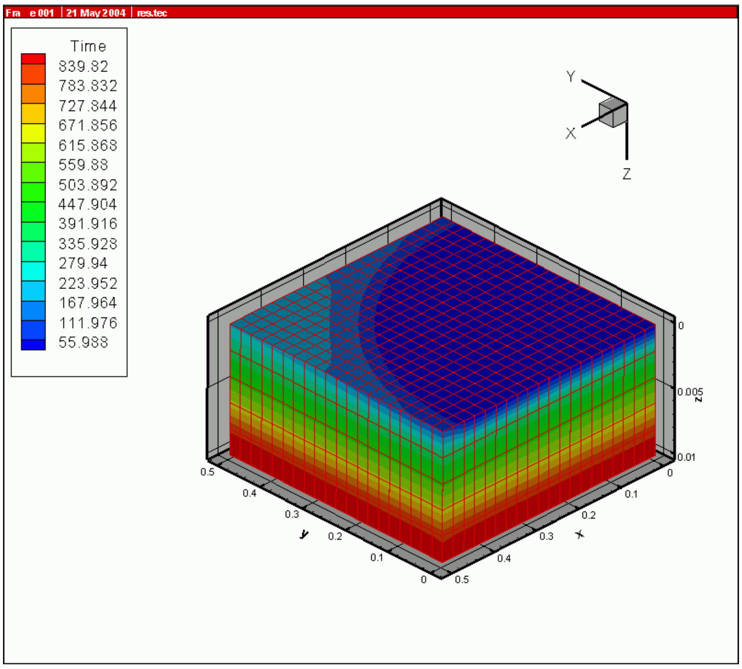

Figure 9. *Resin flow during CRTM injection into rectangular plate. Contour borders represent position of resin flow-fronts*

With this model one can conduct parametric studies related to the CRTM process. The resin flow is influenced by a number of parameters. Some of them are related to the design of mold and its kinetics, such as the gap width and rate of closing, while others depend on material – for example, the preform permeability and its dependence on preform deformation. All of the above mentioned parameters can be modified in the simulation. Some might be actually determined as a part of process design.

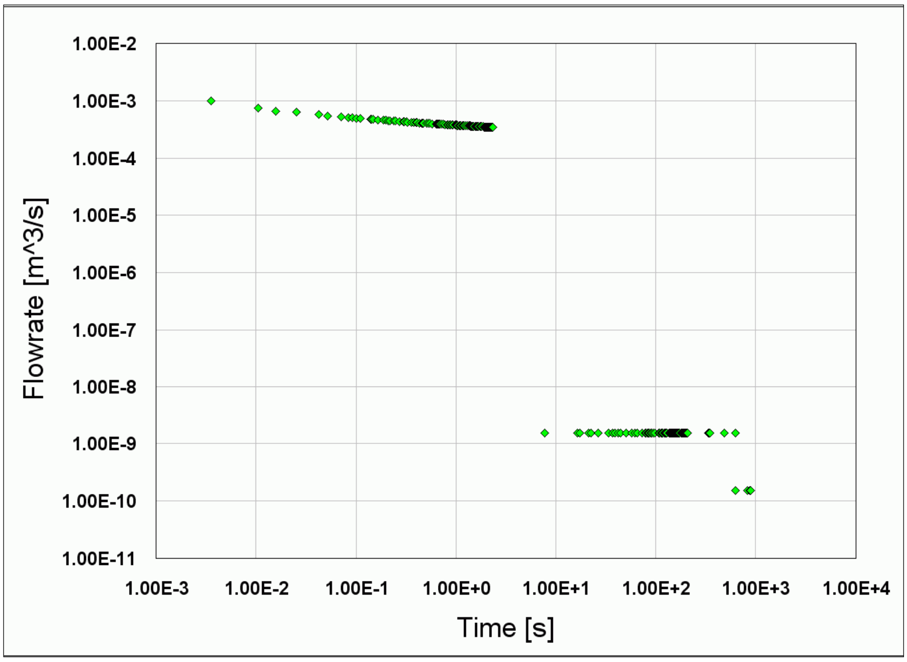

Figure 10. *Resin flow rate at the gate location during CRTM injection into rectangular plate (logarithmic scale). Three phases of process are quite visible, but the actual injection takes place only during the first one. The flow rates during the remaining phases represent resin displaced by the gap and preform deformation*

First, the preform permeability relative to the gap permeability may become an important issue. We can approximately relate this ratio *P* to the gap width by

$$\mathrm{P} = \frac{h^2}{12K_{zz}} \qquad [22]$$

The effects of decreasing this factor from the original value of $2.1.10^6$ to $2.1.10^4$ to $2.1.10^3$ are shown in Figures 11 and 12. The preform permeability was increased by two or three orders of magnitude to values of 10^{-10} m^2 and 10^{-9} m^2, respectively. These values are more realistic for a preform with 30% fiber volume fraction. The in-plane permeability was scaled by the same factor. The flow character changes quite significantly in this range, highlighting the role of modeling.

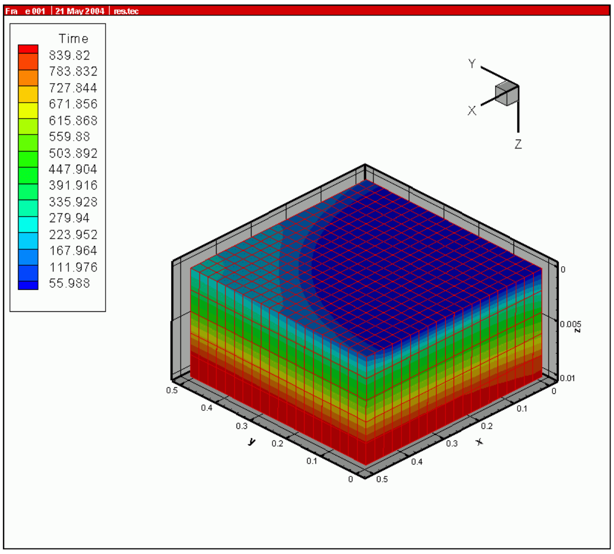

Figure 11. *Resin flow during CRTM injection into rectangular plate. Contour borders represent position of resin flow-fronts. Preform transverse permeability increased to* 10^{-10} m^2 *and the in-plane permeability scaled by the same factor*

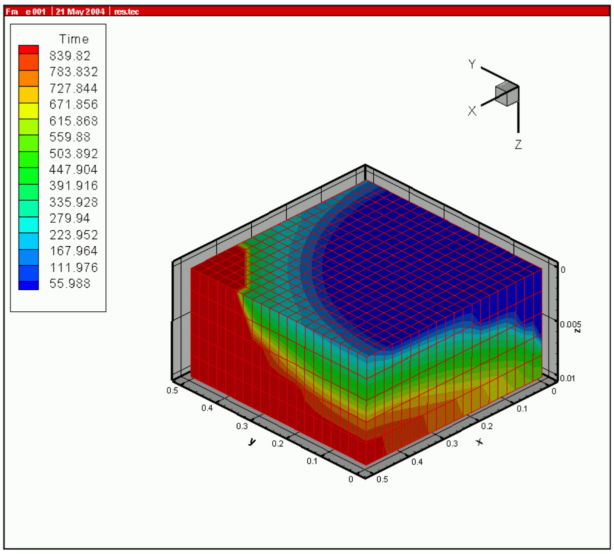

Figure 12. *Resin flow during CRTM injection into rectangular plate. Contour borders represent position of resin flow-fronts. Preform transverse permeability increased to* 10^{-10} m^2 *and the in-plane permeability scaled by the same factor*

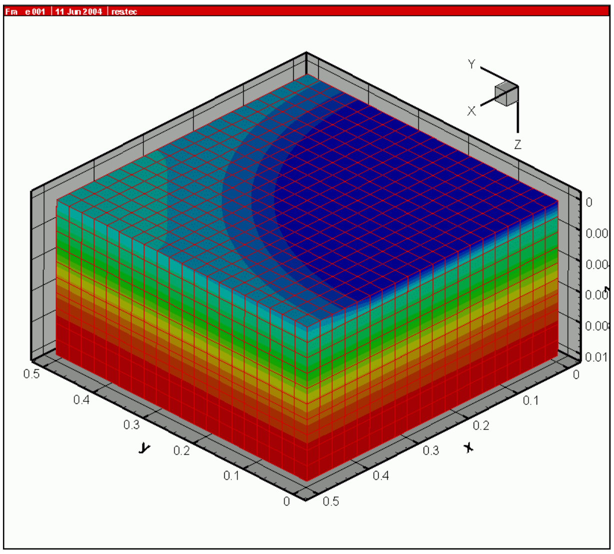

Figure 13. *Resin flow during CRTM injection into rectangular plate. Contour borders represent position of resin flow-fronts. Gap thickness 5mm*

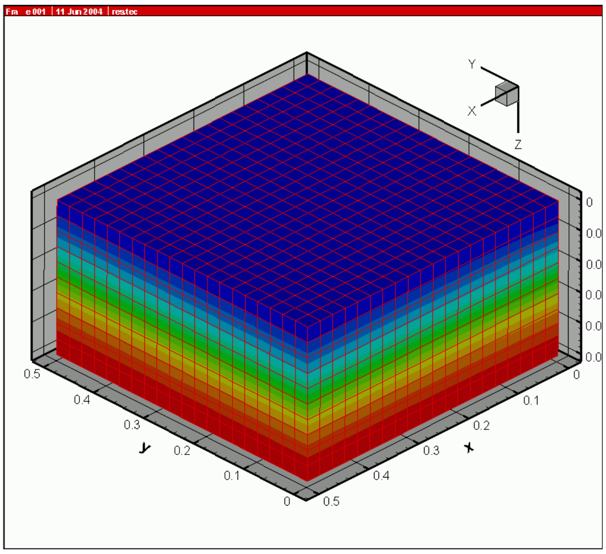

Figure 14. *Resin flow during CRTM injection into rectangular plate. Contour borders represent position of resin flow-fronts. Gap thickness 2mm*

The factor *P* in [22] can be also changed by modifying the gap size. Figures 13 and 14 compare the flow-fronts for gap size of 5 mm and 2mm, all other values being as stated in Table I. Note that the mesh is refined in through-the-thickness direction. In the later case, the resin needs to penetrate well into the preform before the injection is stopped which renders the flow to be purely one-dimensional in through the thickness direction.

This phase may be modeled using a simple 1D model. However one needs to first establish guidelines by modeling as to under what parametric values this may be acceptable in terms of accuracy.

6. Conclusions

The compression-RTM presents an interesting hybrid LCM technique. Since it aspires to high production rates for good quality parts, the process modeling should play a very important role in both the part and the process design.

To model the preform saturation phase of this process is essential to ensure

1. The full preform saturation;
2. Right amount of resin being injected and minimal losses;
3. To provide some feedback on forces necessary to accomplish the process.

The paper describes modifications to an existing simulation code that are necessary in order to provide an industrial strength modeling capability. It also shows how it is possible to successfully model the CRTM manufacturing process using the existing simulation packages for RTM and VARTM. The basis for this approach is the creation of flow sources in the filled areas that are being compressed. The magnitude of these sources has to match the amount of resin that is being forced out by the volumetric compression. Additionally, the material properties have to be incrementally modified as the preform undergoes deformation during processing. This is best accomplished with simulation packages that support scripting and on-the-fly parameter modification, but it might be actually performed on step by step basis by modifying the data file(s).

The implementation based on these principles was demonstrated to work, though a few issues, such as the resin volume conservation, remain to be addressed. More importantly in the long run, the numerical performance of this approach leaves much to be desired. Nonetheless, this approach can be considered to be a temporary solution to the need to model CRTM. as it allows one to model CRTM without additional code development. It also provides a possibility to examine how the CRTM process depends on various parameters and in this way it may prove valuable in formulating the proper simulation procedures for dedicated CRTM modeling code.

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